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ENHANCEMENT OF HUMAN PERFORMANCE IN MANUAL TARGET ACQUISITION AND TRACKING

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This report presents a review and analysis of research literature pertaining to human performance in manual target acquisition and tracking tasks. The emphasis of the review is the identification of factors which enhance performance, particularly those related to training and practice. Three major areas are reviewed: 1) typical patterns of performance in simple target acquisition and tracking tasks; 2) the effects of various training and practice regimens on the development of tracking proficiency; and 3) the impact of dual-tasks conditions on performance of tracking tasks. A framework for interpreting the various theoretical constructs and empirical findings covered in the literature is offered. This framework is based on the general notion of response organization, and embraces both the process of organization and the result of that process.
A major issue which has not been addressed in the research literature is how the impact of dual-task conditions on response organization may be lessened (or recovery hastened) by appropriate training. An experiment was conducted to address this issue. The whole-task

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condition of interest was one in which a primary tracking task was first performed alone, followed by concurrent performance of the primary task and a simple target acquisition task. Three groups of subjects were given different training programs for the whole task. One group was given whole-task training; that is, they practiced the task in training exactly as it was performed in transfer conditions. The other groups practiced the two component tasks separately; they differed in that one group ~~received~~ twice as much practice on the target acquisition task as the other group. The results indicated there was a part-task training advantage for performance of the target acquisition task; both part-task groups performed the component significantly better than the whole-task group in transfer conditions. The extra practice given to one of the part-task groups did not provide any additional advantage. The part-task training advantage was somewhat short lived, however, and had largely dissipated by the last block of trials in the transfer conditions. The results also indicated there was a whole-task training advantage for performance of the primary tracking task and that this advantage grew more pronounced across blocks in the transfer conditions. Fine-grained analyses of response organization in the primary task revealed that a different organization was characteristic of dual-task performance, as compared to single-task performance, and that this alternate organization was better developed in the whole-task group than in the part-task groups. The groups did not differ in response organization or overall proficiency in single-task performance of the primary tracking task. These results suggest that performance of a complex tracking task in dual-task conditions may require a response organization which differs from the organization that develops in single-task practice; thus, dual-task practice may be necessary for the development of an appropriate response organization.

SUMMARY

A literature review which included tracking studies conducted from various theoretical perspectives over several decades was performed. Three major areas were emphasized: (1) typical patterns of response in simple target-acquisition and tracking tasks; (2) development of tracking skill under various conditions of training and practice; and (3) the impact of dual-task conditions on tracking performance. A framework for interpreting the various theoretical constructs and empirical findings was presented. This framework is based on the notion of response organization. Based on the empirical findings, as interpreted within this framework, the following principles of response organization were inferred:

1. Responses become organized by the degree and type of predictability in the input signal. The term predictability refers to the operator's ability to anticipate changes in the signal, not a purely mathematical calculation of uncertainty.

2. Response organization can be characterized in the spatial and temporal domains. These two domains are not independent, but temporal organization tends to develop before spatial organization, regardless of the extent of organization possible in either domain.

3. The most important property of the input signal, with respect to response organization, is bandwidth. Changes in the input signal which occur too rapidly may demand responses which are beyond human capabilities. An implicit assumption of the principles in the following discussion is that required responses are within the operator's limitations.

4. If a task does not permit effective anticipation of responses in time, then the extent of response organization is quite limited. Behavior in these tasks is aptly described as reaction to observed error; the operator's manipulation of the control device tends to lag behind changes in the input signal.

a. Temporal organization in these tasks is limited to a decrease in response latency. Response latency tends to approach the well-established limits on human reaction time (e.g., 200-300 ms for manual response to a visual stimulus).

b. Spatial organization is limited to a refinement of the amplitude (accuracy) of responses. If a variety of response amplitudes are required, the observed amplitudes of the initial response tend to regress toward the mean required amplitude. For example, if the input function is an irregular step function, the operator will tend to overshoot the small step sizes and undershoot the larger step sizes.

c. Inability to effectively anticipate responses in time may result from inherent unpredictability in the input signal with respect to time <u>and</u> space, or from changes that are so gradual or infrequent that the operator cannot time the responses accurately.

5. Effective anticipation of responses in time is facilitated by the provision of preview on the display. If a preview is not provided, then effective anticipation can arise from sufficient experience with a repetitive waveform

such as a sine wave. The extent of experience required increases with the complexity of the waveform.

6. If a task does facilitate effective anticipation, then the responses will not tend to uniformly lag behind the input signal. The responses will tend to produce a closer correspondence between changes in the input signal and changes in the output signal than is obtained from moment-by-moment reactions to the input signal. The nature of the response organization is determined by the extent and type of predictability in the input signal.

a. If both the direction and amplitude of input signal changes are highly predictable, but the temporal pattern is highly unpredictable, then anticipation will occur, although it may be relatively inaccurate in time. The duration of intervals between responses will tend to regress toward the mean of the intervals between input signal changes. For example, if the input function is a step function that is spatially predictable but temporally irregular, then the operator will tend to lead the long-step durations and lag the short-step durations.

b. If the temporal pattern is highly predictable and the spatial pattern is at least predictable with respect to direction, then anticipation will develop quickly and will be quite accurate. Spatial accuracy may show little if any improvement with practice, unless a quite extensive practice regimen is used.

7. As task unpredictability is increased, its impact, in terms of disrupting response organization, may increase disproportionately. At moderate levels of unpredictability, response anticipation may be largely suppressed. That is, the effect of the unpredictability may be more pronounced than would be predicted by extrapolation from lower levels of inherent unpredictability.

This interpretive framework made it possible to predict how the process of response organization is affected by the type and extent of predictability in the task, and how those effects are reflected in the correlation matrices based on extended practice of a task. Briefly, we argued that the process of response organization produces a superdiagonal form in the correlation matrix. We predicted that the development of response organization is evidence by a pattern of increasing correlation coefficients in the first off-diagonal of the matrix, up to a point where the magnitude of these correlations stabilizes and then exhibits no further upward or downward trends. The point at which the correlations stabilize represents the point at which response organization stabilizes. We also predicted that the magnitude of the correlations in the first off-diagonal will systematically vary as a function of task unpredictability. Another prediction was that the extent of practice required for these correlations to stabilize will systematically vary as a function of the complexity of the predictable task components.

Review of the dual-task literature revealed that performance of a tracking task is almost invariably degraded if a concurrent task is added. The theoretical accounts of this performance decrement have tended to focus on the notion of time-sharing. In terms of response organization, the one relevant study we reviewed suggested that the response organization is severely disrupted by dual-task conditions, and that performance reverts to moment-by-moment corrections.

The study was not clear whether this disruption could be remedied by further practice in dual-task conditions. We entertained two possibilities: (1) the disruption caused by a second task might be lessened if the primary task is extensively practiced alone, thereby allowing response organization to stabilize; or (2) the response organization which develops in single-task practice might actually be inappropriate for dual-task performance, thereby rendering dual-task practice essential for the development of a response organization which accommodates both tasks.

A small-scale experiment was conducted, designed to allow at least a preliminary assessment of theoretical and practical issues raised by the possibilities pointed out earlier. A whole-task condition was created in which a complex tracking task, which facilitated response organization, was performed alone at the beginning of the trial, followed by concurrent performance of the primary task and a simple target-acquisition task which did not facilitate response organization. Three groups of subjects performed this whole task in transfer conditions; they differed in that they had received different training regimens on the previous day. One group received whole-task training; they practiced the whole task exactly as it was to be performed on the following day. The other two groups practiced both component tasks separately on the first day; one of these groups received twice as much practice on the target-acquisition task as compared to the other part-task group.

The results indicated that the groups were roughly equal in proficiency on the primary task during the single-task segment of performance. The whole-task group had an advantage in proficiency on the primary task during the dual-task segment, and this advantage increased throughout performance on day 2. The part-task groups had an initial advantage in proficiency on the target-acquisition task, but this advantage decreased across performance on day 2. Further analyses were performed on the primary tracking task data, to assess response organization in the single- vs. dual-task segments of a trial, and to assess differences among the groups in response organization. The timing of responses in each segment was assessed, and over all groups it was found that dual-task performance was characterized by fewer numbers of responses which were in synchrony with the input signal, and greater numbers of lead errors, lag errors, and instances in which no response was made (as compared with single-task performance); this alone was not surprising. However, when the correlations among the frequencies of each response type and overall performance were examined as function of trial segment (single- vs. dual-task) and group, an interesting pattern was found. In the single-task segment, better performance was highly correlated with higher numbers of synchronous responses, and lower numbers of leads, lags, and omissions. This pattern was equally true for all groups. In the dual-task segment, however, better performance was highly correlated with higher numbers of synchronous responses and leads, and lower numbers of lags and omissions. This pattern suggested that the subjects learned to improve performance by committing lead errors, perhaps to accommodate shift of visual attention to the target-acquisition display. However, this pattern is descriptive of the whole-task training group only. One part-task training group did not show this pattern, except that the number of leads was positively correlated with performance. The other correlations were very low, suggesting that their responses in the dual-task segment were not well organized. The other part-task group seemed to be somewhat better organized, but not nearly to the extent exhibited by the whole-task group.

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INTRODUCTION

The pilot of a modern tactical aircraft must perform a number of complex psychomotor tasks during the course of a mission. The basic task of maintaining controlled flight certainly has complex psychomotor components, and in some types of missions, the pilot may be required to perform other psychomotor tasks while maintaining flight control. For example, a common profile for a low-altitude air-to-ground mission calls for the pilot to fly close to the terrain while navigating to a predetermined point, then ascend ("pop") to a somewhat higher altitude, acquire and track the intended ground target, release the appropriate weapon, and finally to descend again close to the terrain for egress. During the time spent at the higher altitude, the aircraft is more vulnerable to detection and engagement by enemy air defense systems. It is desirable, therefore, that the tasks required for successful target acquisition and tracking be performed as rapidly and efficiently as possible, without sacrificing accuracy of weapons delivery.

Many studies of target acquisition have concentrated on visual factors such as acuity and eye-movement (scan) patterns. These factors are undeniably important. However, many weapon systems also require manual control (typically of a joystick) for successful acquisition and tracking. Newer, more sophisticated systems often include automatic acquisition and tracking functions, but these functions are subject to error and may require manual assistance by the human operator to acquire the correct target and/or to maintain accurate target tracking. In a single-seat aircraft, these manual tasks must be performed by the pilot while maintaining flight control. Factors that affect the manual aspects of target-acquisition and target-tracking tasks are the primary concerns of this research.

Some target-acquisition and target-tracking tasks of interest here may be relatively simple when considered alone. A common arrangement is one in which a joystick controls the orientation of a sensing device--for example, a television camera. The camera may be located underneath the aircraft, or, in some cases, in an air-to-ground missile. The associated display is simply the image captured by the camera, often with a symbolic sight (e.g., crosshairs) superimposed on the image in the center of the display. The associated task is thus a simple compensatory tracking task; that is, the operator's task is to null any deviation between the target and the fixed representation of the sight. The control system is typically first-order (rate control). Initially, the sensing device may be slightly out of line with the desired target, requiring that the orientation of the sensor be adjusted so the target is brought to the center of the display, coincident with the sight. At this point in many systems, the operator presses a switch which initiates automatic tracking of the sighted target. Then the operator monitors the display and uses the joystick to correct any significant drift of the target from the sight.

Other aspects of target acquisition and tracking are obviously quite complex. In many types of missions, the pilot is expected to perform a high-precision maneuver (to help minimize exposure to enemy defenses), which must result in a near-boresight alignment of the aircraft and the target. A second high-precision maneuver may be performed after the target is acquired. The manual activities required for these high-precision maneuvers must be coordinated and accurate. Furthermore, some weapons systems require that the operator continue to manually aid the target-tracking functions during the second maneuver. Thus, there are two major types of manual tasks which are of great importance in target acquisition and tracking: the highly precise and coordinated manual aspects of flight control, and the relatively simple manual tasks involved in aiding the automated acquisition and tracking functions. The fact that, in a single-seat aircraft, the pilot may be required to simultaneously perform these tasks is of particular concern in this research.

Although the specific manual control requirements vary across aircraft, weapons systems, and missions, the tasks just described are representative of the potential complexity of manual activities during target acquisition and tracking. Various types of manual acquisition and tracking tasks have been studied in previous research. Three relevant areas that have received particular attention are as follows: (1) typical patterns of performance in simple acquisition tasks and in compensatory tracking tasks, (2) the effects of various training and practice regimens on tracking proficiency and skill organization, and (3) the effects of dual-task conditions on performance of tracking tasks. Each of these areas is reviewed. A special emphasis throughout the review is the identification of conditions and techniques which enhance performance. The review embraces studies conducted from various theoretical perspectives over several decades. An attempt is made to provide a coherent framework for interpreting the theoretical constructs and empirical findings of these diverse approaches.

LITERATURE REVIEW

Typical Patterns of Performance

Acquisition

Acquisition tracking, also called step tracking, is a task in which a sudden (or initial) discrepancy between the target stimulus and a response marker (e.g., a cursor) must be nulled by the operator. The time required to acquire the target has been widely studied. Total acquisition time is typically divided into three segments: (1) reaction time--the time from the onset of the discrepancy to the initiation of a control movement; (2) primary movement time--the duration of the first control movement, which usually nulls most of the discrepancy between the target and the marker; and (3) correction time--the time from the end of the primary movement until the target and marker are in stable alignment. Brown and Slater-Hammel (6) analyzed these components of acquisition time in a task in which the direction and distance of movement were varied. They found no difference in reaction time which could be attributed to either factor. Primary movement time was found to vary as a function of distance, but not as a function of direction. Correction time was found to be somewhat faster for the smallest distance used in their experiment than for

longer distances, but no further differences in correction time were observed. The mean reaction time in their experiment was about 250 ms, which is typical of reaction time to a visual stimulus as measured from the onset of the stimulus to the initiation of the response. Poulton (27) reported that reaction times do not tend to vary as a function of step size unless the step is unexpectedly small or unexpectedly large.

The average primary movement times in the Brown and Slater-Hammel (6) experiment ranged from about 200 ms for a 2.5-cm (1 in.) step size to about 550 ms for a 40-cm (16 in.) step size. Thus, the primary movement time for the 40-cm (16 in.) step was roughly twice that of the 2.5-cm (1 in.) step, whereas the actual size of the step differed by a factor of 16. This difference indicates that the rate of movement was faster for the larger step sizes. Taylor and Birmingham (29) described typical patterns of movement rate in an acquisition tracking task. They found that the movement rate tends to increase rapidly during the first part of the movement, reaching its maximum value nearly halfway through the movement. The rate of movement then gradually decreases throughout the second half of the movement. Craik and Vince (7) found similar patterns of movement rates for a variety of step sizes. Although faster maximum rates were found for larger step sizes in both these studies (6, 7), the primary movement times were reliably longer for larger steps. Thus, the increase in movement rate for larger steps does not fully compensate for the actual difference in distance.

Craik and Vince (7) also analyzed the accuracy of the primary movement. As mentioned earlier, the primary movement typically nulls most of the error between the target and the marker. They found that the magnitude of the remaining error is typically proportional to the size of the step. This relationship is often called "Craik's ratio rule." The obtained proportions are typically between 5% and 10%. Poulton (27) reported that "Craik's ratio rule" does not hold for very small movements. Vince (30) also demonstrated that the value of the proportion can be manipulated through instructions which emphasize either speed or accuracy over the other. Taylor and Birmingham (29) reported that the tendency for the primary movement to undershoot vs. overshoot the target is related to the size of the step. They found that undershoots (i.e., the magnitude of the movement was too small) tended to be associated with large step sizes, whereas overshoots were typically found for small steps. These tendencies must be interpreted as errors of central tendency within a given experiment (27), because a given step size may be relatively small in one experiment, but relatively large in another. Thus, the tendency to overshoot or undershoot is largely associated with the range of step sizes used in an experiment rather than the actual size of the step.

Control system sensitivity (gain) apparently has little effect on primary movement time if the control device is a joystick or lever, although it does have an effect if the control device is a knob or handwheel that must be rotated (7, 27). Control system sensitivity may have a pronounced effect on correction time. Hammerton (14) examined the effects of control system sensitivity on both primary movement time and correction time. He found no difference in primary movement time across the various levels of sensitivity used, but did find correction time to markedly increase for the higher levels of sensitivity. Thus, if sensitivity is high, it may be more difficult to make the precise adjustments required to bring the target and marker in stable alignment

than if the sensitivity is moderate. Poulton (27) recommended that, for a joystick position (zero order) control, the optimum sensitivity may be obtained by equating the maximum displacement of the stick and the maximum required movement of the response marker.

Higher-order control systems tend to produce longer acquisition times. Acquisition time with a rate (first order) control may be nearly twice as long as with a comparable (in terms of obtainable movement rates) position control, and acquisition time with an acceleration (second order) control may be as much as 7 times greater than with a comparable rate control (27). These differences are, in part, due to the additional control movements required to stabilize the display. In a rate control system, two control movements are required to move the marker (or target, if a compensatory display is used) from one stable position to another. The first control movement establishes the rate of movement of the marker, and the second movement is required to null the movement rate back to zero. In an acceleration control system, three movements are required to move the marker from one stable position to another. Not only do these additional required movements take more time, but they also introduce additional opportunities for errors, in that they must occur at appropriate points in time. If the additional required control movements in higher-order systems are off in time or in magnitude, then the correction time component of acquisition tracking is bound to be increased.

Compensatory Tracking

In a compensatory tracking task, the response marker remains in a fixed position on the display. The target stimulus moves about by some input function which creates a discrepancy between the positions of the marker and the target. Thus, the term compensatory literally refers to the nature of the display. With a compensatory display, no preview of the to-be-tracked function is possible, although, if the function is predictable (e.g., a sine function), then anticipation of the correct response may be possible. If the input function is unpredictable, the operator can only respond to an observed discrepancy between the position of the marker and the target. One problem with a compensatory display is that the operator cannot readily distinguish between discrepancies that result from the input function and those that result from incorrect control movements (27), unless the input function is fully predictable. Thus, typical patterns of performance vary as a function of the form of the input function.

If the input function varies over time in an unpredictable manner, then the operator is forced to react, moment by moment, to observed error. The most important property of an unpredictable signal, with respect to tracking accuracy, is the signal's bandwidth (23). If the low-frequency cutoff is fixed near zero and the bandwidth is varied by selecting different high cutoff points, then a typical pattern of results is for tracking error, integrated or summed over time, to be rather stable for bandwidths below about 0.6 Hz, but to increase rapidly as a function of higher bandwidths. With bandwidths above about 1.0 Hz, the operator's control movements may actually create more error than they eliminate (23), indicating that the operator is unable to track the signal at all. Somewhat better performance is obtained with pursuit displays for bandwidths between 0.6 Hz and 1.5 Hz.

An input function describing the total of several sine waves appears to be highly irregular and is difficult for an operator to predict, even though it is exactly determined mathematically. The operator can learn the average properties of the input function and then use these properties as a basis for anticipating changes in the input function (25). Performance under these conditions may be a mixture of anticipation of the average form of the input function and reaction to observed irregularities. The anticipation of the input function may be highly inaccurate, particularly if the function contains fairly high-frequency components.

When the form of the input signal is both fully predictable and relatively simple (e.g., a single sine wave), then the operator may be able to track the signal by producing a pattern of control movements synchronized with the input signal. Pew (23) reported that, for sine waves with frequencies between 0.75 Hz and 1.5 Hz, operators were able to achieve this synchronization with little difficulty. For frequencies below about 0.5 Hz, however, the operators appeared to make moment-by-moment corrections instead of generating the sine-wave pattern. For frequencies above about 1.7 Hz, the operators had a difficult time keeping up with the pace.

Performance of a compensatory tracking task is apparently a mixture of responding to observed error between the marker and the target, and generating a pattern of control movements based on the expected properties of the input signal. The contribution of each mode of performance depends on properties of the input signal. For signal waveforms that are highly unpredictable or that have a low frequency, the error-correcting mode dominates typical performance. The pattern-generation mode is dominant if the signal waveform is highly predictable and has a moderate frequency. The notion of two response modes is related, but not identical, to the notion of closed-loop and open-loop mechanisms in tracking. The error-correcting mode may be seen as a closed-loop mechanism in which the perceived magnitude of error is the feedback in the loop. When the error magnitude surpasses some threshold, a control movement is initiated to null the error. The pattern-generator mode may be seen as an open-loop mechanism in which a series of patterned movements is generated for some period of time without modification due to feedback. A more detailed analysis reveals that the correspondence between the two sets of terms is not perfect. In the error-correcting mode, once the control movement is initiated, it may be largely ballistic, depending on its duration (30). Occlusion of vision during very brief control movements (less than about 500 ms) has little effect on accuracy. The possibility that proprioceptive cues might provide feedback during control movements was considered by several investigators (3, 31, 32). The results from these studies indicate that proprioceptive cues can be effective for some types of movements, but their value as feedback is limited. Fitts (9) argued that the control of movements is limited by a fixed information-processing capacity of central mechanisms rather than the availability of feedback. Thus, brief control movements may be entirely ballistic, and longer movements may be intermittently ballistic. It may be appropriate to think of error-correcting mode as a 2-level hierarchy in which the outer loop is closed and the inner loop is open. Similarly, pattern-generation mode need not be seen as entirely independent of feedback. Pew (22) demonstrated that patterned responses on a tracking task were systematically modified by the pattern of residual (i.e., uncorrected) errors. Thus, it may also be appropriate to think of pattern-generation mode as a 2-level hierarchy with a closed outer loop and an open inner loop.

Effects of Training and Practice

The development of a training program must address two fundamental issues: (1) what behaviors are to be trained, and (2) how those behaviors are to be trained. In addressing these issues, the characteristics of the task in the situation of interest must be carefully analyzed, and the characteristics of individuals to be trained must be assessed. One of the important outcomes of these processes is a clearer understanding of the need for training, and consequently the goals of training. One goal of human factors engineering is to reduce training costs by designing equipment and procedures that are well suited for human use (18). Thus, one important issue is whether the need for training can be reduced (or eliminated) by better equipment design. Given that a need for training on a manual tracking task exists, the goals of training must be determined with reference to the desired behaviors in the situation of interest. In this context, questions such as whole-task vs. part-task training must be framed and relevant empirical findings interpreted. The outcome of a training needs analysis might reveal, for example, that performance of a manual tracking task under ordinary conditions requires little training beyond familiarization, but performance under extreme or unexpected conditions does require training. Another possible outcome is that the tracking task requires little training, but performance of the task while simultaneously performing other tasks does require training. A variety of training procedures for tracking tasks have been studied; most are variations of the part-task training method. Few studies, however, have included a statement of the goals of the procedure in terms of the specific aspects of performance that are expected to benefit from training.

Part-task vs. Whole-task Training

If a tracking task is sufficiently complex, it may be possible to identify one or more components of the task that can be performed separately. A training regimen may be established in which the task components are practiced separately for a period of time, followed by performance of the entire task for a period of time. Such a regimen is called part-task training. A part-task training procedure has two potential benefits: (1) performance of the whole task may be better if the task components are practiced separately than if the whole task is practiced for a comparable period of time, and (2) substantial savings in training costs may be realized if the part-task regimen is effective and is less expensive than whole-task training. Thus, a part-task training procedure may be desirable even though it is not as effective as a whole-task procedure, if it is sufficiently effective and substantially less expensive than whole-task training. Part-task training may be particularly attractive for tasks performed by aircrews, given the high cost of aircraft and the costs associated with logistical support and expendables such as fuel. The cost-benefit of part-task training, however, must be assessed in the context of some existing or proposed training program. The more salient issue here is whether part-task training, as compared to whole-task training, tends to result in better performance of complex tracking tasks.

Wightman and Lintern (35) reviewed part-task training methodology and results from previous studies of part-task training for tracking tasks. They identified three major classes of procedures used in extracting components of a task for separate training: segmentation, fractionation, and simplification. A segmentation procedure extracts a task component based on temporal or spatial

characteristics. For example, some complex tasks may be considered as a series of identifiable subtasks. If one (or more) of these subtasks is crucial to overall performance, or is particularly difficult, then it may be advantageous to train this segment of the task separately. Fractionation is similar to segmentation, except that it extracts two or more identifiable subtasks which must be performed simultaneously. These subtasks are then trained separately. Fractionation might be advantageous for subtasks which are difficult to learn together, but once mastered, are not difficult to perform together. Fractionation could be counterproductive, however, if the crucial element in overall performance is how well simultaneous subtasks are coordinated or time-shared. This issue is explored in more detail in the discussion on dual-task tracking studies. Simplification procedures extract a subtask by adjusting, or perhaps eliminating, one or more characteristics of the task. For example, a time lag in a control system might be reduced or eliminated to facilitate learning other control system dynamics.

In their review of empirical results, Wightman and Lintern (35) found segmentation procedures to be particularly promising. Three of the four segmentation studies reviewed showed a clear advantage for part-task training. Furthermore, each of the three segmentation studies which found a part-task training advantage used a backward-chaining technique to segment the task. Backward chaining is a technique in which the last component in a sequence is practiced first. Preceding components in the sequence are successively added until finally the entire sequence is practiced. Part-task training based on fractionation procedures was not found to be promising. Of the six fractionation studies reviewed, only one showed an advantage for part-task training. Wightman and Lintern (35) criticized the approaches used to extract the subtasks for part-task training. Only one of the six studies used a systematic method to identify crucial subtasks for training, and it was that study which found the part-task training advantage. Part-task training based on simplification procedures produced mixed results. In general, techniques which reduced ambiguity about the effects of control movements during training were found to be promising for subsequent performance of a compensatory tracking task. This observation is in accord with Poulton's primary criticism of compensatory displays (27): the operator cannot readily distinguish the effects of control movements from the effects of the input function when a compensatory display is used. Wightman and Lintern were also critical of the lack of systematic methodology in deciding which task characteristics to simplify in part-task training. They noted that a variety of task characteristics could be manipulated to adjust task difficulty, possibly leading to different results. The selection of some task characteristics (e.g., control order) for simplification, without a basis in a systematic task analysis or in psychological theory, is unwarranted, and obtained results may add little to the understanding of how to enhance the training of tracking skills.

Other Training Issues

Although part-task training procedures are most commonly proposed techniques for complex psychomotor tasks, other techniques have been considered. One class of these techniques is called adaptive training. In adaptive training, some aspect of the task is continuously or frequently modified as a function of the trainee's performance (16). Adaptive training is predicated on the assumption that training is most effective when the difficulty of the task is

at an appropriate level. Thus, the task is made more difficult as the trainee becomes more proficient. Implementation of the procedure requires two important specifications: the performance measure which is taken to reflect the trainee's current proficiency, and the characteristic of the task which is to be manipulated to make the task more or less difficult. The function or logic that relates these two items (i.e., how much change in task difficulty is to be associated with a given change in performance) must also be specified. Poulton (27) reviewed studies which have employed adaptive training on a tracking task. He concluded that adaptive functioning is not effective if the order of the control system is manipulated, because strategies and response patterns that are more effective for a given control order are not effective for a higher or lower control order. Other techniques, such as varying the amplitude or frequency of the input signal, may be more effective, but Poulton points out that it is not possible to assess the value of adaptive training unless the best forms of both adaptive and fixed training can be identified and compared.

Another technique that has received some attention is the use of augmented feedback during training. There is inherent feedback in most tracking tasks--the operator can see how well he or she is performing by virtue of the magnitude of error between the target and the marker. Feedback from kinesthetic senses may also be of use to the operator. Additional feedback may be useful if the quality of the display is degraded such that the magnitude of the error is not clear. Additional feedback may also be effective when there is no problem with the display; it may serve as a reinforcer. Summary feedback at the end of each trial in an experiment appears to be an effective technique. Other techniques that have been examined include presentation of auditory cues when the magnitude of error is acceptably small, and providing a display of error rate or acceleration. Although these techniques may be somewhat effective, they apparently have no advantage over an end-of-trial summary (26).

Development of Tracking Skill Under Extended Practice

When a tracking task is performed repetitively, it is no surprise to find that performance tends to improve. A simple way to represent the improvement in performance is to plot performance against time; that is, to plot the learning curve. The plot of the learning curve may be quite deceptive if the performance measure is not carefully chosen. Bahrick et al. (4) showed that learning curves based on the amount of time that error is below some criterion value will markedly differ for different values of the criterion. They recommended that root mean square error (RMSE) be used as the performance measure. Poulton (27) agreed that RMSE is the best overall measure of tracking, but pointed out that RMSE is a gross measure that does not reflect subtle differences in performance. That is, nearly identical RMSE scores may be obtained from patterns of performance which are quite different. Tracking errors stem from two sources: spatial errors (control movements are off in magnitude and/or direction) and temporal errors (control movements are incorrectly timed.)

Analysis of the temporal and spatial component of tracking error, in addition to analysis of gross error measures, provides valuable insight regarding the development of tracking skill with practice. Merrill Noble et al. (21) analyzed the acquisition and organization of tracking skills in five groups. The tracking tasks given to the five groups differed in their predictability. The input function for the tracking task was an irregular step function which

consisted of 12 steps, and task predictability was set by the percent (100, 83, 75, 67, or 0) of the steps which were repeated each time the task was performed. The task was performed a total of 320 times by each subject over the course of several practice sessions and 80 more times 3 months later. They used integrated absolute error (which is highly correlated with RMSE) as their gross performance measure and developed specific indices of temporal and spatial errors. They also found that, by the end of the practice sessions, the integrated error was highly correlated with task unpredictability, and the differences between adjacent conditions were about equal.

Their next analyses of temporal and spatial errors revealed quite different trends for the groups. They classified timing errors as leads (movement began too soon) or lags (movement began too late). They found, not surprisingly, that the subjects performing the highly predictable tasks tended to make proportionally more lead errors, and hence less lag errors, than did the subjects who performed the less predictable tasks. They also found that performance of the 67%-predictable task was not much different from performance of the 0%-predictable task. The subjects in the 67% group were far less likely to commit lead errors than the performances of the 75% and 83% groups would predict. This pattern indicates that a relatively high degree of predictability is required for the pattern-generation mode of responding to dominate the error-correction mode in this type of task. This interpretation is supported by examining the mean duration of lag errors. For both the 0% and 67% groups, the mean duration of lags was just under 200 ms, which is about the same as typical reaction times to visual stimuli, whereas the mean duration of lag errors for the other groups was much lower.

The analysis of spatial errors indicated that the magnitude of undershoots and overshoots tends to <u>increase</u> throughout the early stages of practice, and then decrease later with practice. This finding was taken to indicate that it is skill in the timing of responses that is developed early in practice, whereas skill in controlling the amplitudes of control movements does not improve until late in practice. In their study, however, there was no temporal uncertainty; the tasks differed only in spatial uncertainty. Later research (reviewed by M. Noble and Trumbo (20)) examined the effects of temporal uncertainty in a task with no spatial uncertainty. Temporal uncertainty was manipulated by the number of step durations in the sequence that were fixed, analogous to the procedure described earlier. Analysis of overall performance revealed that performance was better on the highly predictable sequences than on the less predictable sequences after a practice regimen of 40 trials. Finer-grained analyses of temporal errors during practice showed that subjects in all groups tended to commit lag errors in the early stages of practice, but by the end of practice, the subjects performing the highly predictable sequences showed a greater tendency to commit lead errors than did the subjects on less predictable sequences. Furthermore, toward the end of practice, subjects in all conditions showed a tendency to lead the long-duration steps and lag the short-duration steps. That is, the temporal pattern of responses tended to regress toward the mean step duration.

Other investigators have used correlational techniques to study the development of tracking skills. The correlations among performance measures at various stages of practice and scores on other tasks are calculated. Factor

analysis techniques are often used to explore the nature of changes in tracking performance over practice. A common finding is that the correlation matrix for tracking performance at various stages of practice tends to have a superdiagonal form (15). The essential characteristic of this pattern is the correlation of performance on a given trial with performance on other trials decreases as the number of intervening trials increases. For example, performance on trial 5 is more highly correlated with performance on trial 6 than it is with performance on trial 7, and so forth. No particular magnitude of the differences is necessary. This pattern is typical of many types of skilled performance (15). Clyde Noble (19) had 500 subjects perform a standard Pursuit Rotor tracking task for 100 trials, and the resulting correlation matrix largely followed the superdiagonal form. Although this pattern of results is quite typical, no theoretical explanation of the pattern has gained wide acceptance. The superdiagonal form does indicate, however, that the relative differences among individuals, with respect to tracking performance, do not change dramatically from trial to trial, but may change substantially over the course of many trials. The form also indicates that performance in the early stages of practice may not be a good predictor of performance in later practice stages.

Fleischman and his colleagues used factor analytic techniques to study the development of a variety of psychomotor skills over the course of practice (10, 12). In considering this research, it is necessary to first note the distinction between the terms "ability" and "skill" as used in their research. The term ability refers to a general, stable trait of an individual that may impact performance on a variety of tasks, whereas the term skill refers to proficiency on a single task or small group of highly related tasks (11). An individual's level on a given ability is not expected to appreciably change over the course of a study. The relationship between ability levels and development of skill with practice is the object of interest in their research. To state it another way, changes in the factor structure of the practiced task are used to describe the development of skill on that task. Abilities are established statistically as common factors in a battery of reference tests, which may include printed tests and psychomotor tasks. In his study of the Pursuit Rotor tracking task, Fleishman (10) had subjects perform the tracking task for 15 trials. A reference battery of 17 tests was also administered. He used the 8 odd-numbered trials out of the 15-trial sequence as measures of tracking proficiency. The intercorrelations of the tracking measures and the reference tests were factor analyzed. Eleven factors were extracted using the centroid method and were graphically rotated. The orthogonality of the factors was preserved in the rotation. He found two factors which were associated with the tracking task only; that is, none of the reference tests had high loadings on these factors. One of these factors was more strongly associated with the early stages of practice, and the other was more strongly associated with the later practice stages. He interpreted the factor associated with the later practice stages as representing skill on the tracking task. He speculated that the factor associated with the early practice stages may have represented a "learning set" which helped facilitate performance early in practice, but then diminished in importance as the tracking skill developed. Of the factors defined by the reference battery, only two had any systematic relationship with the tracking measures. The Control Precision Factor, interpreted as the ability to make controlled movements involving the large muscle groups, was found to have a fairly stable relationship with tracking measures across the trials. This factor was strongly associated with the Complex Coordination Test and the Track

Tracing Test in the reference battery. The second factor defined by the reference battery which was also related to the tracking measures was called Rate Control. This factor had a moderate association with the early stages of practice, but had low association with the late stages of practice. Several other factors were associated with various tests in the reference battery, but none had strong associations with the tracking measures. The major problem with such an analysis is that the factors which were interpreted as abilities were forced to be mutually orthogonal, even though there was no reason to assume that an individual's levels on various abilities were uncorrelated. As a consequence, it is difficult to interpret the ability factors and to understand their relationship with tracking proficiency. An oblique factor solution might well have been more meaningful.

Clyde Noble (19) summarized four theoretical positions which have been offered in correlational studies as accounts for the development of psychomotor skills. According to the simplification viewpoint exemplified by Jones (15), extended practice on a psychomotor task produces a progessive decrease in the number of abilities that are related to performance of that task. In other words, the proportion of variance in psychomotor performance that can be accounted for by performance on other tasks <u>decreases</u> as a function of practice. An alternate viewpoint, also espoused by Jones in a later work (16), is that there are simultaneous processes of simplification and complication which affect changes in performance over practice. If the task is quite simple, then the complication process does not occur, but with more complex tasks, simplification characterizes the early stages of practice and complication dominates the later stages. A fair interpretation of this position is that the simplification process represents the emergence of the uniqueness of the skill, whereas the complication process represents the subsequent unfolding of the complexity and organization of the skill. A third theoretical viewpoint is represented best by Fleishman's position that different combinations of abilities are important at different stages of practice. Contrary to Clyde Noble's interpretation (19), Fleishman's position does not imply that a complication process is at work; Fleishman's position predicts that the factor structure of the task will <u>change</u> with practice. A progressive change toward a more complex structure is not required by Fleishman's position. The fourth theoretical position, associated with Adams (1), is that the combination of abilities which affect performance does not change with practice, but the relative importance of each ability may change. Furthermore, a unique skill (unrelated to any other abilities) may arise if the task is complex; this unique skill is thought to be related to the particular pattern of responses required by a given task. A task might tap a variety of basic perceptual and motor abilities, but the sequence and pattern of the perceptual and motor activities may be unique to that task.

Clyde Noble endorsed the simplification viewpoint. He tried to reconcile the various theoretical viewpoints by noting that both Jones' simplification-complication hypothesis and Adams' emphasis on the uniqueness of response patterns predict that the task-specific variance in a psychomotor task will increase with practice. (Task-specific variance for a given stage of practice is variance which can be accounted for by performance of the same task at other stages of practice, but not by performance on tests in a reference battery.) His major criticism of the simplification-complication hypothesis was that it does not offer predictions that differ from the predictions of the simplification-only viewpoint; thus, the latter was preferred in the interest of parsimony.

He considered the correlations between tracking proficiency and reference battery measures, which change as the tracking task is practiced, to be interesting in their own right, but not enlightening with respect to understanding the development of psychomotor skill. The important trend, according to Clyde Noble, is that the proportion of variance accounted for by the whole reference battery decreases with practice, while the task-specific variance increases with practice.

Clyde Noble overlooked the fact that Jones' simplification-complication hypothesis was not a reversal of his previous endorsement of the simplification viewpoint, but instead was an elaboration of it. The simplification component of the hypothesis refers to the changing relationship between performance on the task of interest and reference battery measures as a function of practice. The complication component refers to the relationship between performance of the task at a given stage of practice with performance at other stages of practice. Thus, the simplification component does refer to task-specific variance, but the complication component refers to task-specific covariance. The simplification-complication hypothesis was offered as an account for why some tasks exhibit a strong superdiagonal trend in the correlation matrix and others do not. Jones (16) noted that the superdiagonal form is characteristic of complex tasks, but is less characteristic of simple tasks. He reasoned that, for simple tasks, no organization of skill is required. The relative differences between individuals are established after a few practice trials. For more complex tasks, however, much more practice is required for the individual differences to stabilize. If the superdiagonal form of correlations is taken to reflect a complication process, then the amount of practice over which the form persists should be a function of the complexity of the task. This interpretation is in accord with Adams' notion (1) that the uniqueness of a complex task is the patterning of component responses required for proficiency on that task. Adams also raised a further possibility: Each individual could have a general facility in patterning the components of a complex task, and, if so, then there should be a stronger relationship between an individual's well-practiced performances on two complex tasks than between the performances of those tasks early in practice, if the tasks are reasonably similar.

An Interpretation of Experimental and Correlational Findings

With many topics in psychology, it is somewhat difficult to relate findings from experimental studies of a topic with findings from correlational studies of the same topic. As Cronbach (8) noted, these two approaches represent distinct traditions in psychology. The approaches tend to be concerned with different aspects of performance and to emphasize different sets of independent variables. The experimental approach emphasizes differences among means; the correlational approach emphasizes differences in accountable variance about those means. The two approaches tend to use different terminology in describing the same phenomena, and the analytic techniques employed are certainly different. The topic of tracking is no exception. The experimental research reviewed earlier was largely concerned with differences in tracking proficiency among groups as a function of practice and stimulus conditions, whereas the correlational research was chiefly concerned with changes in the variance-covariance structure of tracking proficiency as a function of practice. But, Cronbach (8) argued, a more complete account of a topic requires contribution from both research approaches. That is, a theory or model which can describe how typical

performance (means) varies as a function of conditions, and can also describe systematic ways in which individuals differ under those conditions (variances and covariances), is to be preferred over a description of either aspect alone. With tracking proficiency, the situation is further complicated by the existence of two distinct areas of inquiry within the experimental approach. Adams (2) discussed these two areas at length, noting that applied experimental research has concentrated on machine-centered variables such as the design of displays and controls, the order of the control system, and so forth. Basic experimental research, on the other hand, has concentrated on procedural variables such as amount and spacing of practice, and the effect of instructions. But Adams' objections were not focused on the differing emphases of the two areas; rather, they were directed toward the lack of attention given to how machine-centered variables and procedural variables might interact. Adams particularly admonished applied researchers to consider the effects of procedural variables in the interpretation and generalization of their results. To Adams' remarks it could be added that the potential three-way interactions among machine-centered variables, procedural variables, and organismic variables has received even less attention than the two-way interaction.

A principal difficulty in simultaneously considering empirical results from basic experimental, applied experimental, and correlational studies is that they tend to use widely different explanatory constructs in interpreting their respective findings. The basic experimental findings are discussed in terms of learning curves, central processing mechanisms, motor programs, and similar constructs. The applied experimental findings are often discussed in engineering terms such as closed-loop vs. open-loop mechanisms, and one-integrator vs. two-integrator systems. Correlational findings are expressed in terms of patterns in correlation matrices, and the factor structures which can be derived from those patterns. Nevertheless, it is possible to at least attempt to interpret the various findings within a single framework. An example of such an attempt is as follows:

A tracking task, according to Adams (2), is a task in which an input signal defines a motor response for the operator. The response is executed by manipulating a control device. The control mechanism, which includes the control device and may consist solely of that device, generates an output signal. The difference between the two signals is tracking error, and the operator's performance is measured as some function of that error over time. Given this definition, it is clear that tracking performance is a joint function of properties of the input signal, properties of the control mechanism, and properties of the operator. The properties of the input signal which have been shown to affect performance include the manner in which the signal is displayed (27), the signal bandwidth (23), and the degree of uncertainty associated with changes in the signal (20). The uncertainty associated with changes in the signal may be expressed with respect to time and space, and spatial uncertainty may be further expressed with respect to direction and amplitude. Different patterns of uncertainty, with respect to time, direction, and space, have different impacts on performance (20). Properties of the control mechanism which have been shown to affect performance include the order of the control system (27), certain characteristics of the control device such as physical resistance (3), and the extent to which the output of the control system appreciably lags behind the operator's control movements in time (27). Properties of the operator which have been demonstrated to have a relationship to performance include the operator's

performance of certain other tasks (10); the operator's previous experience with the tracking task, and levels of proficiency during that previous experience (1); and certain demographic properties, such as gender (19); which are undoubtedly important, but are of less interest in the discussion at hand. This list of properties is not exhaustive but is representative of conditions which have been studied.

The operator's behavior under many of the combinations of conditions studied may be aptly described as moment-by-moment reaction to perceived tracking error. The operator's manipulation of the control device under these conditions tends to lag behind changes in the input signal, and the magnitude of the lag is roughly the same as the latency of human reactions to other types of stimuli in other tasks. Under certain special conditions, however, the operator's behavior does not tend to lag behind changes in the input signal. The operator tends to manipulate the control device in a way that produces a close match between changes in the input signal and changes in the output signal with respect to both time and space. The operator's behavior under these conditions is more aptly described as the emission of a series of responses which are well organized in time and space. The extent to which this description adequately characterizes behavior may vary; it is perhaps more accurate to say that the operator's behavior may be characterized by a description selected from a continuum anchored by "moment-by-moment" reaction and "well-organized responses." The identification of input signal, control system, and operator properties which are associated with well-organized responses is of great theoretical and practical interest.

The concept of well-organized response patterns has been discussed in several ways. Some researchers have focused on the process of organization; others have focused on the results of that process. To extract the common themes from the various lines of research reviewed, it is necessary to first examine the implications of the term "response organization," and then to consider the different aspects of this concept which have been addressed--theoretically and empirically--by various researchers. The fundamental implication of the term is that responses which are well organized produce a closer correspondence between changes in the input and output signals than do responses which are less well organized. A second implication is that the results of well-organized responses, when repeated several times, are more consistent than the results of less-organized responses. A third implication is that response organization must develop with appropriate practice and then stabilize as it approaches some asymptote.

The terms used by various authors to describe well-organized responses reflect the various aspects of response organization that have been addressed. Adams (1) used the term "response patterning," and noted that the activities which must be patterned include the perceptual and cognitive activities required by a task besides the motor activities. His emphasis was that various components must be organized into a sequence and the uniqueness of the combination of components, and their temporal sequence, determines the uniqueness of a skill. Poulton (24) referred to 3 types of anticipation: (1) receptor anticipation, which may be provided by a preview of the input signal; (2) effector anticipation, which essentially is a preview of the output signal (as in a predictive display); and (3) perceptual anticipation, which arises from previous experience with a relatively predictable task. His emphasis was on the sources of

information which facilitate response organization. Pew (23) distinguished between pattern-generation mode and error-correction mode, emphasizing the qualitative and quantitative differences between well-organized responses and moment-by-moment reactions. The currently popular terms are motor programs and motor schemas (28). The term motor program emphasizes the importance of central processing mechanisms in structuring the response sequence before it is executed, and also that the sequence can be correctly executed without continuous feedback. The term motor schema emphasizes the flexibility of the response organization under different environmental demands, and the importance of feedback in the central mechanisms which compare the intended and actual results of a response sequence. The terms used to describe the process of organization also reflect different aspects of response organization. Several researchers, including Clyde Noble (19), have discussed response organization as the elimination of irrelevant responses. This term implies that the response components which become organized are the components required by the task, and other components, such as unnecessary movements, tend to disappear with practice on the task. Fleishman (11) emphasized the change in the factor structure of a task over practice. Finding a task-specific factor which increases in importance over practice is common in his research. This factor represents the tendency for performance of a complex task to become less related to performance on other (reference) tasks, and also to become more consistent with practice. Jones' processes of simplification and complication (16) also reflect these tendencies.

Given that the theoretical constructs described earlier are appropriately interpreted as references to different aspects of response organization, it is instructive to consider the empirical findings from the various lines of research and to infer underlying principles of response organization. Although the account offered later is incomplete, it will be argued that there is a systematic pattern of results across various studies, and the principles of response organization may be derived from this pattern. Attention is focused on properties of the input signal which facilitate response organization, and the interaction of input signal properties with extent of practice. Although properties of the control mechanism are undoubtedly important in response organization, there apparently has been little research which assessed performance with different control mechanisms over extended practice.

Various properties of the input signal have been demonstrated to have an impact on response organization. Apparently, the most important property of the signal in this regard is its bandwidth (23). Changes in the signal which occur too rapidly may demand responses which are beyond human capabilities. Given that the input defines responses which are within a person's limitations, the extent to which changes in the input signal can be anticipated or predicted by the operator has a major impact on response organization. A technique which greatly enhances response organization is simply to provide a preview of the signal. With preview, changes in the input signal can be directly anticipated by the operator, as can the responses required by those changes. Preview provides the basis for what Poulton (24) called receptor anticipation, and the amount of preview which is effective depends on the signal bandwidth (23). If no preview is provided, then response organization is enhanced by the properties of the input signal which can be predicted by the operator. These properties facilitate what Poulton (24) called perceptual anticipation, and it must be emphasized that the predictability of the signal is determined with respect to

the operator, not a purely mathematical calculation of uncertainty. In general, complex wave forms are more difficult for an operator to predict. Simpler wave forms--such as a single sine wave, a regular triangle wave, and a regular step wave--are more easily predicted by the operator and hence facilitate response organization. (One exception to this principle is that even simple wave forms do not facilitate response organization if the period of the wave is too long, as Pew (23) noted.) If the operator is unable to predict the exact properties of the input signal, then response organization can be based on the average or typical properties of the signal. This is demonstrated by the tendency to undershoot large step sizes and overshoot small step sizes in tasks where spatial irregularities in the input signal are used (29), and by the tendency to lead long-step durations and lag short-step durations in tasks where temporal irregularities are used (20). A factor which apparently moderates response organization with predictable wave forms is the extent to which the responses demanded by the input signal are gradual and/or continuous, as opposed to sudden and/or discrete (27). Responses which are sudden tend to be less accurate than those which are gradual; responses which are discrete tend to be less accurate than those which are continuous. Thus, according to the fundamental implication of response organization, as discussed earlier, the less accurate responses must be considered less organized.

The nature of the unpredictability in the signal has an impact on the resulting response organization. Signal unpredictability can be expressed with respect to time and space; similarly, response organization can be characterized temporally and spatially. Different mixtures of temporal and spatial unpredictability have different impacts on the temporal and spatial aspects of response organization. Spatial unpredictability can be further specified with respect to direction and amplitude. Based on the research reviewed by Merrill Noble and Trumbo (20), it appears that a high degree of predictability with respect to direction is necessary for response organization. Predictability with respect to direction alone, however, is not sufficient. If the signal is highly predictable with respect to direction and time, or direction and amplitude, then overall performance will be better than if direction alone is predictable. Although overall performance was equivalent for the direction-plus-time and the direction-plus-amplitude conditions, the fine-grained analyses reported by M. Noble and Trumbo reveal quite different patterns of performance between the two conditions. The subjects in the condition with no temporal predictability, but fixed direction and amplitude patterns, tended to commit lead errors on about half of their responses. The magnitude of their errors in timing increased early in practice and remained fairly constant thereafter. This trend suggests that the spatial components of their responses were well organized, but that their temporal organization was based on the average duration of the steps in the input signal. The subjects in the condition where time and direction were fixed, but amplitude was unpredictable, showed a decrease in the magnitude of timing errors over practice, indicating that the temporal organization of their responses was well developed.

The common trend in the various studies discussed earlier is that responses will become organized if they are within human capabilities and if they can be anticipated. Furthermore, the nature of the organization is determined by the degree and types of predictability present in the task. We will argue later that the degree and types of predictability also determine the extent of practice required for the organization to emerge and stabilize. We will also argue

that these factors are reflected in the patterns found in correlation matrices which are based on extensive practice of a task.

If a task is so unpredictable that responses cannot be beneficially anticipated, then the responses will continue to fit the descriptions of moment-by-moment reactions. The response organization will be quite limited. Temporal organization is limited to a decrease in response latency. This decrease occurs rapidly and approaches the well-established asymptote of 200-300 ms (7). The spatial organization is limited to a refinement of the accuracy of response amplitude. The observed response amplitudes tend to regress toward the mean required amplitude with practice (29). The movement rates tend to be organized so that they partially compensate for different response amplitudes (7, 29). The correlation matrices based on practice of these types of tasks will show a weak superdiagonal form (16). The superdiagonal form will likely be characteristic of the early stages of practice (i.e., the upper left corner of the matrix), but will dissipate in later stages of practice. A reasonable prediction is that the extent to which the superdiagonal form persists is a function of the spatial complexity of the responses. The temporal and spatial organizations of the response are interrelated in at least one way: Changes in the input signal which are uncharacteristically large or small will produce a longer response latency (27).

In tasks which facilitate anticipation of responses, the responses will become organized on the basis of the type of predictability in the task (20). Tasks which have high spatial predictability, but low or moderate temporal predictability, will tend to produce responses which are well organized spatially. The temporal organization tends to be based on the mean duration of the time intervals between changes in the input signal; the times between responses tend to regress toward this mean. This regression toward the mean tends to occur early in practice and then stabilizes. A reasonable prediction is that uncharacteristically long or short intervals between signal changes might disrupt the spatial organization of the response to those changes, analogous to the interrelationship between temporal and spatial organization discussed earlier. Tasks which have high temporal predictability, but moderate spatial predictability, will tend to produce responses which are well organized in time. The tendency to regress toward the mean duration of intervals between input changes will be less pronounced. The spatial organization in these tasks develops much more slowly.

A common trend for all types of tasks is that temporal organization tends to stabilize before spatial organization. In tasks which do not permit anticipation, temporal organization is limited to a decrease in response latency. This decrease occurs early in practice. In tasks which have high spatial predictability and low temporal predictability, the temporal organization is based on the mean duration between signal changes. This organization emerges early in practice and stabilizes as spatial organization continues to develop. Tasks with high spatial and temporal predictability tend to produce responses which are well organized temporally; spatial organization lags behind temporal organization in these tasks (21).

In tasks which do permit response anticipation, the extent of practice required for response organization to stabilize is a function of the degree of predictability in the task. Tasks in which predictability is provided by a

preview of the input signal require less practice for response organization to emerge than tasks with predictability which must be learned through experience. For tasks with predictability which must be learned, the extent of practice required for response organization to stabilize is a function of both the complexity of the pattern to be learned and the degree of inherent unpredictability in the pattern. Obviously, the response organization in these tasks is based on the perceived regularities in the input signal; hence, the organization cannot stabilize until some point after the learning of the pattern is as complete as possible. If the pattern to be learned is quite simple--for example, a simple sine wave or step with no irregularity--then the pattern will be obvious almost immediately (23). The learning of more complex patterns is apparently enhanced by the use of a pursuit display instead of a compensatory display, presumably because the compensatory display confounds the changes in the input signal with errors in control movements (27). The presence of inherent unpredictability in the signal may result in a pronounced disruption of response organization. In the step tracking task used by Merrill Noble et al. (21), the step function in which exactly two-thirds of the steps were fully predictable did not produce better performance than a completely random function until well over 500 practice trials.

Jones (16) reported that correlation matrices based on extended practice of a complex task tend to exhibit superdiagonal form over longer periods of practice than those based on practice of a simple task. The interpretation offered here is that the persistence of the superdiagonal form is associated with tasks which facilitate response anticipation. (We acknowledged that the superdiagonal form may also characterize practice on tasks which do not facilitate response anticipation, but which do involve complex sequences of actions in responding.) If the superdiagonal form is a result of response organization over practice, then it is possible to deduce the extent of practice required for response organization to stabilize from other patterns in the correlation matrix. Recall that the only requirement for superdiagonal form is that the correlation coefficients progressively decrease in magnitude across rows (and down columns, since the matrix is symmetric), starting with the element on the main diagonal (which is always 1.0). But if the superdiagonal form is a consequence of response organization, then it is possible to predict definite trends to be found in the first off-diagonal of the matrix. (To clarify terms, the first off-diagonal in the matrix contains the correlations of trial 1 with trial 2, trial 2 with trial 3, ..., trial N - 1 with trial N, in an N x N correlation matrix. The second off-diagonal contains the correlation of trial 1 with trial 3, trial 2 with trial 4, and so forth.) One implication of the notion of response organization, as discussed earlier, is that performance should become more consistent with practice. Another implication is that the organization should stabilize after some sufficient extent of practice. If the outcome of responses becomes more consistent with practice, then it is implied that performance on a given trial becomes a better predictor of performance on the next trial as practice proceeds, up to the point when the response organization stabilizes. Beyond this point, the relationship between performance on a given trial with performance on the next trial should remain fairly constant. These implications can be assessed by examining the trend in the first off-diagonal of the correlation matrix. The coefficients in this off-diagonal should become progressively larger (reflecting the increasing consistency in performance from trial to trial), up to some critical point. Beyond this critical point, there should be no further upward or downward trends (reflecting

the stabilization of organization), although minor fluctuations up and down may appear.

The correlation matrix presented by Clyde Noble (19, p. 368) was calculated on the performance of the pursuit rotor task over 20 blocks of 5 trials each. The correlation matrix is based on average performance within each block, and was obtained from a sample of 500 subjects. The superdiagonal form persists throughout the matrix. By the predictions offered earlier, elements along the first diagonal increase steadily up to a critical point (block 7 with block 8), and beyond this point there are no further trends upward or downward. Further predictions can be derived from the interpretive framework offered earlier, regarding patterns in the higher off-diagonals and the factor structure which can be obtained from the matrix, but a full explication of these predictions is beyond the scope of this report.

We noted that the interpretation offered earlier predicts that the magnitude of the correlations in the first off-diagonal reflects the extent of response organization at each point in practice, and that the magnitude of the correlation at the stability point reflects the degree of response organization permitted by the task. We further suggested that the magnitudes of the correlations in the first off-diagonal should systematically vary as a function of task <u>unpredictability</u>, and that the extent of practice required for the first off-diagonal correlations to stabilize should systematically vary as a function of the complexity of task <u>predictability</u>. That is, tasks which are highly predictable should produce larger correlations in the first off-diagonal than tasks which are less predictable, and tasks in which the predictable components of the signal are more complex should require more practice for the first off-diagonal correlation to stabilize than tasks with predictable components which are simple. Unfortunately, few of the studies reviewed include the correlation matrix in their results; thus, it is not possible to test these predictions with reported findings. Clearly, these predictions need empirical verification.

<u>Effects of Dual-Task Conditions</u>

Tracking tasks have been quite popular in dual-task studies, perhaps because performance on a tracking task tends to be quite sensitive to the addition of a second task. One common use of the dual-task paradigm is to assess "spare capacity" or "residual attention" in studies of workload. The rationale is that performance of two concurrent tasks will show a decrement on one or both of the tasks when their combined demands exceed the capacity of the operator. By manipulating characteristics of one of the tasks (e.g., visual vs. auditory inputs) and comparing the effects of these characteristics on dual-task performance, investigators have attempted to identify which types of tasks impose relatively higher workload. This effort has been of particular interest since the advent of speech input-output technology in aircraft cockpits. Another reason for the popularity of tracking tasks in dual-task studies is that piloting an aircraft is, in many ways, a complex tracking task, and much applied research has been driven by concern about pilot performance in high workload conditions.

Performance on a tracking task tends to be degraded when a second task is added. Poulton (27) reviewed over 24 studies of tracking in dual-task conditions and classified each one on the basis of the instructions given to subjects

regarding the priorities of the two tasks. He found that performance on the tracking task tended to show a reliable decrement if the instructions gave priority to the other task. He also found that tracking tends to show a decrement if the instructions were to give equal priority to both tasks, or if no priority instructions were given. For studies where the instructions gave priority to the tracking task, Poulton found that tracking performance did not show a decrement if the second task did not compete for visual attention and if the responses for the second task were vocal. In studies where separate visual displays were used for each task, or where the second task required a manual response, performance of the tracking task still showed a decrement, even though the subjects were instructed to give priority to the tracking task.

Theoretical accounts of the decrement have tended to focus on the notion of time-sharing. Time-sharing has different connotations for different theoretical positions. For theories which view the human as a single-channel information-processing system, time-sharing implies that attention is switched back and forth between tasks, and a performance decrement occurs whenever the switching cannot occur fast enough to keep up with the processing requirements of each task. Time-sharing is seen as a characteristic of individuals, in that some people can switch faster than others. An alternate viewpoint is that there are multiple processing resources, rather than a single channel, and that these resources must be shared by the two tasks (33). A performance decrement occurs whenever the two tasks compete for a given resource. This model accounts for the finding that performance on a visual-manual tracking task need not suffer if the second task is auditory-vocal, by proposing functionally distinct resources for visual vs. auditory inputs, and for manual vs. vocal responses. This principle has been extended to a proposition of distinct resources for central processing of spatial tasks and central processing of verbal tasks, and it is further proposed that the combinations of visual input--spatial processing--manual output, and auditory input--verbal processing--vocal output, respectively, are more efficient and compatible than other arrangements (34). Time-sharing efficiency is suggested to be enhanced by the design of tasks which conform to the more compatible configurations. A primary issue in time-sharing research is whether an individual's facility for time-sharing is a general ability which impacts performance on a variety of dual-task combinations, or instead is a special skill which arises after practice on a given dual-task combination.

The impact of dual-task conditions on response organization in tracking tasks has been given little attention. Garvey (13) studied the development of tracking proficiency in single-task conditions over 25 days of practice, followed by 3 days of dual-task performance, with a different secondary task on each day. He described his results in terms of an analog computer model. He found that, at the beginning of practice, subjects performed analogously to a 1-integrator system with a feed-forward loop, but after extended practice, performance was analogous to a 2-integrator system. When the secondary task was added, performance reverted to the 1-integrator analogy which characterized initial performance. The second integrator in Garvey's model may be interpreted as the emergence of a well-developed temporal organization in responding. If so, then his results imply that, under dual-task conditions, the response organization is disrupted and performance reverts to moment-by-moment corrections (the 1-integrator system). It is not clear, however, whether the disruption in response organization could be remedied by further practice in dual-task conditions.

Two intriguing possibilities come to mind regarding possible interactions of single- vs. dual-task conditions and practice, with respect to response organization. One is that practice under single-task conditions is important for the emergence and stabilization of response organization, and that the disruption of a second task is lessened if the responses are well organized. The recovery of response organization, to the extent possible, might be hastened if the responses were well organized before dual-task conditions were imposed. The alternative is that the response organization which develops under single-task practice could actually be inappropriate for dual-task conditions. The dual-task conditions might require a tracking task to be performed in a different way to obtain satisfactory performance on both tasks. In either case, it is clear that the response organization for a tracking task must accommodate the demands of a second task. The question is whether the accommodation of the second task is achieved by developing a stable and efficient organization in single-task conditions, thereby permitting easier accommodation of a second task, or whether the second task must be accommodated by the development of an organization which integrates the requirements of the second task with those of the tracking task. If the first explanation holds, then dual-task performance should be enhanced by single-task practice. If the second explanation holds, then single-task practice beyond mere familiarization should provide little benefit to dual-task performance; dual-task practice would be required for the appropriate response organization to emerge.

The possibility that the response organization required for dual-task performance might be fundamentally different from the organization which develops under single-task conditions is supported, at least indirectly, by the general tendency for part-task training based on fractionation to be inferior to whole-task training (35). It is further supported by the finding of Briggs and Naylor (5) that both whole-task training and progressive part-task training (in which crucial part-task components are combined during training) resulted in better performance in the transfer conditions than either a pure-part procedure or a simplification procedure. The whole-task and progressive part-task procedures both allow practice under conditions where performance on concurrent subtasks must be coordinated.

The issue of whether dual-task performance is enhanced by single-task vs. dual-task practice has important implications for theoretical perspectives on human performance and on practical issues such as training program design. An explicit assumption of many models of dual-task performance is that performance in dual-task conditions is largely a function of proficiency on the component tasks; the debate has focused on the nature and importance of other factors such as time-sharing. A finding that performance in dual-task conditions is enhanced by extended practice in single-task conditions would support this assumption. The alternate finding, that proficiency in dual-task conditions is largely independent of proficiency in dual-task conditions, would certainly require this assumption to be reconsidered. Such a finding would also imply that training programs based on part-task fractionation procedures are likely to be ineffective. The experiment reported next was designed to allow assessment of these possibilities.

EXPERIMENTAL METHOD

Subjects

Twelve right-handed male undergraduate students enrolled in psychology courses at Georgia Tech served as experimental subjects. Subjects were scheduled for testing on two consecutive days. At their first testing session, subjects read and signed an information and consent form which described the tasks and duration of testing. At the conclusion of testing, all subjects received extra credit in their psychology course for their participation.

Tasks

The whole-task condition in this experiment consisted of single-task performance of a primary tracking task for 15 s, followed by dual-task performance of the primary task and a secondary target-acquisition task. The primary tracking task was a pursuit task in which the input signal was determined by the sum of two sine functions. A constant was added and subtracted from this function to form two parallel sinusoids which were displayed on a cathode-ray tube (CRT), giving the appearance of a winding road which scrolled down the screen over time. The response marker (output signal) was a small circle. The vertical position of the circle was fixed at the center of the display; the horizontal position was determined by the movement of a joystick in its x-axis. As the roadway moved downward, the subject's task was to move the joystick to position the circle as close to the center of the road as possible. After 15 s, a target array containing a solid circle, square, and triangle was presented to the left of the road. A bell was sounded, signalling the appearance of the target array. The subject examined the shapes and decided if the triangle was bounded by a set of brackets, which represented the sight. If the triangle was inside the sight, the subject continued tracking on the roadway until the trial ended and the screen blanked. If the triangle was not inside the sight, he pressed the button on the joystick which activated the target-acquisition task. Then the subject concurrently performed the primary tracking task and the target-acquisition task, each with a CRT display and first-order joystick control. The general appearance of each display is shown in Figure 1. The right hand was used to perform the primary tracking task; the left hand was used for the target-acquisition task.

The target-acquisition task was displayed on a second CRT located directly below the primary task display. On the display was an expanded view of the three shapes, in the same relative placement, and separated by the same proportional distances as those which appeared next to the road on the primary tracking task. The sight was fixed in the center of the screen. The joystick controlled the horizontal movement of the three shapes as a fixed group such that any of the shapes could be placed under the sight, but the distances between the targets and their position relative to each other remained constant. The subject entered this target-acquisition task only if the position of the triangle required adjustment for it to appear under the sight. The subject corrected the position of the triangle and then firmly pressed the button on the target-acquisition joystick as quickly as possible. A bell sounded to indicate that the button had been sensed, representing the initial acquisition of the target. Then a random function was used to perturb the position of the target from side to side, resulting in an occasional drift of the target away

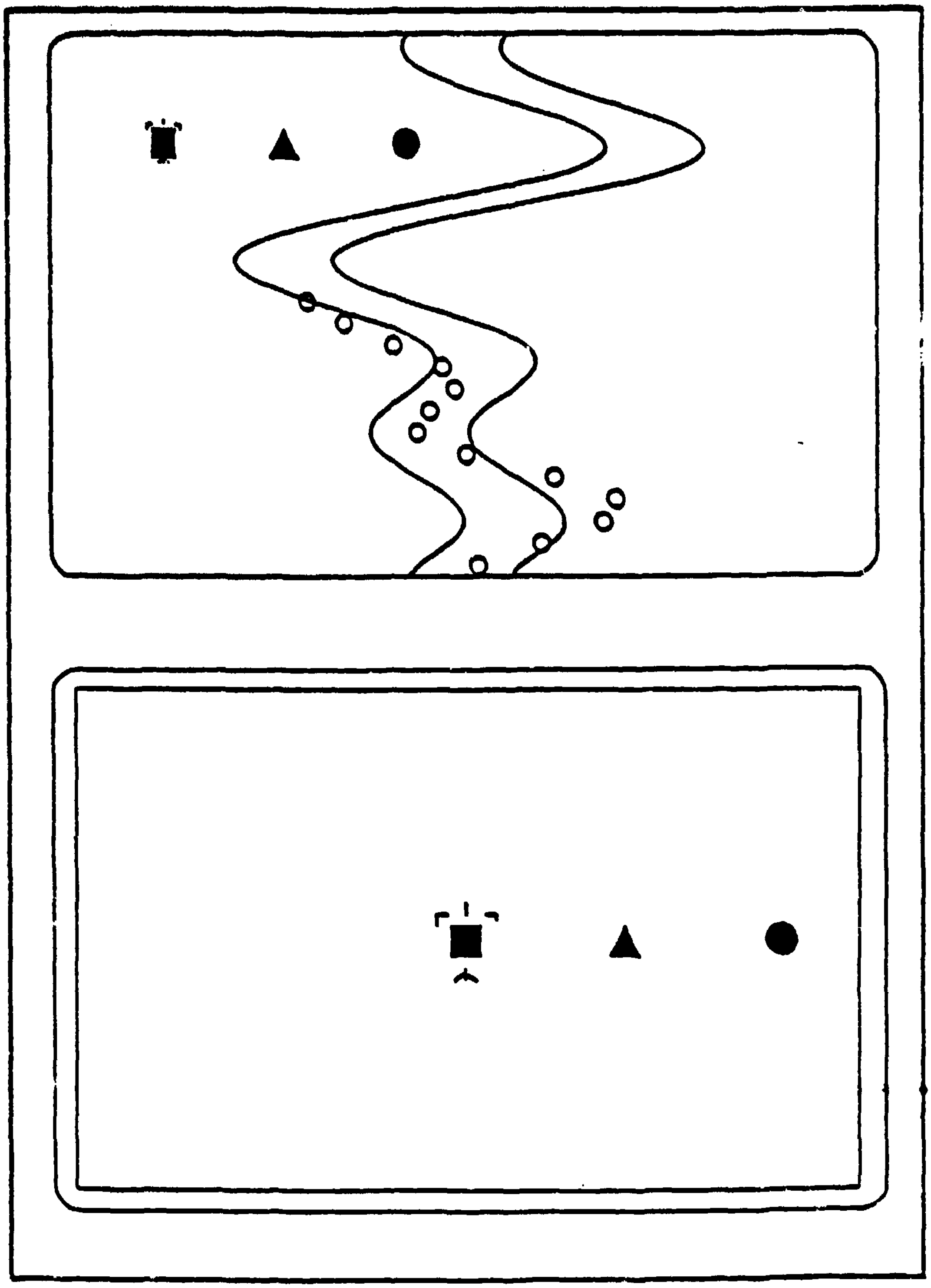

Figure 1. Configuration and general appearance of displays.

from the sight. The subject's task was to null these drifts as quickly as possible.

The subjects were instructed to examine the target array presented on the primary display and to decide if performance of the target-acquisition task was required. They were also instructed to stabilize the position of the response marker on the primary task before initiating the target-acquisition task. They were told that initiation of the acquisition task could be performed at any point in the 9-s interval between the appearance of the target array at the top left of the screen and its disappearance off the bottom of the screen, and that speed in initiating the acquisition task was not of interest in the study. The subjects were further instructed to perform the initial acquisition as quickly as possible after the initiation of the acquisition task, and to then begin to perform both tasks simultaneously. They were told to consider both tasks equally important during the dual-task segment of a trial. Once initiated, the target-acquisition task continued for 12 s. There was a brief period after the end of the acquisition task in which the primary task alone was active; the duration of this period depended on how quickly the subject initiated the acquisition task.

Subjects receiving part-task training on the two component tasks were presented with the same displays used in whole-task performance, with minor procedural differences. On the primary tracking task, subjects tracked the changing roadway for 30 s without interruption by display of the targets. On the target-acquisition task, at the beginning of each trial, a bell sounded and the screen displayed TRIAL STARTING... Several seconds later, the trial automatically started with the screen display of the three shapes and the target indicator; each trial lasted for 12 s.

Apparatus

Subjects were tested with a sound-attenuated chamber (Industrial Acoustics Co., Bronx, New York) with the door open throughout the experimental testing session. A 30.48-cm (12.2 in.) monochrome CRT display (Zenith Data Systems, Model #ZVM-121) was placed at a viewing height of 110.8 cm (44.3 in.) above the chamber floor. Directly below the monochrome display, a 30.48-cm (12.2 in.) color CRT display (Quadchrome, Model #HX-12) was placed at a viewing height of 81.0 cm (32.4 in.) above the chamber floor. The subject was comfortably seated at a chair height of 44.5 cm (17.8 in.) directly in front of the CRT displays. Joysticks were secured at 29.25 cm (11.7 in.) from the center of the lower CRT display directly to each side. Each joystick was fixed in the center of the y-axis and could move ±30 degrees along the x-axis. A response button was located in the upper left corner of each joystick. Directly outside the sound-attenuated chamber, an IBM PC controlled the primary tracking task on the upper display and an IBM XT controlled the target-acquisition task on the lower display.

Procedure

Subjects were randomly assigned to one of three groups as shown in Table 1. Notice that all groups received identical treatment on day 2: 4 blocks of whole-task performance. On day 1, group 1 received whole-task training and groups 2 and 3 received part-task training. Group 3 differed from group 2 by

receiving twice as much training on target acquisition. On day 1, all subjects read the information and consent form and answered the questions.

TABLE 1. EXPERIMENTAL DESIGN

Group	Day 1	Day 2
1	3 blocks whole task*	4 blocks whole task*
2	3 blocks primary task plus 3 blocks target acquisition	4 blocks whole task*
3	3 blocks primary tracking plus 6 blocks target acquisition	4 blocks whole task*

*The whole task consisted of a segment in which the primary tracking task was performed alone, followed by a segment in which the primary tracking task and target-acquisition task were performed concurrently.

Subjects in whole-task training received a demonstration of the primary tracking task and target-acquisition task separately, and then were shown the two component tasks as a dual task. The following strategy was suggested to all subjects: Center the joystick between trials on both tasks so that the position of the open circle on the upper task and the position of the targets in the lower task would be stable when the next trial began. Subjects were also instructed to correct the bottom task only when the triangle drifted outside the bounds of the sight. Subjects were given 3 blocks of 15 trials each on day 1. Day 2 performance was identical to day 1 training, except that 4 blocks of 15 trials were performed.

Subjects in the part-task training groups received only a demonstration of the primary tracking task and the target-acquisition task separately. Subjects were first given 3 blocks of 15 trials on the primary task, and then were given either 3 or 6 blocks of 12 trials each on the acquisition task. On day 2, subjects in both part-task training groups were given a demonstration of the whole task and the strategies that had been given to the whole-task training group on day 1. They were then given 4 blocks of 15 trials on the whole task.

The position of the targets and the distance between them were randomized within blocks for all subjects. Within each block, 3 trials were given on which no correction of the triangle's position was needed. Twelve trials remained where the subjects needed to perform the target-acquisition task. Of these 12 trials, 6 required movement of the triangle to the left, and 6 required movement to the right. Three distances between targets were used: 2.2 cm (0.88 in.), 3.3. cm (1.32 in.), and 4.5 cm (1.8 in.). The 12 trials were arranged so that each possible combination of direction and distance appeared exactly twice, in

a random order. The 3 catch trials (i.e., the triangle was already sighted) were randomly interspersed with the test trials. The inclusion of the catch trials and the use of the various distance-direction combinations in random order produced a task which was inherently unpredictable with respect to the initial acquisition of the target. The sampling interval for data collection was 274 ms on the primary tracking task and 55 ms on the target-acquisition task.

Rationale

The experiment described earlier permits assessment of a number of issues related to the effects of whole vs. part training on proficiency and response organization. The transfer condition (i.e., day 2) is one in which the whole task requires performance of the primary tracking task both alone and with the target-acquisition task. Thus, proficiency in both conditions is of interest and can be assessed separately throughout practice on day 2. Response organization can also be assessed separately for single-task and dual-task conditions on day 2. The primary tracking task facilitates response organization. The summed sine waves produce a pattern that is easy to learn, and the provision of substantial preview should eliminate any uncertainty associated with changes in the input signal. In contrast, the target-acquisition task does not facilitate response organization. The target array presented on the primary tracking display permitted anticipation of the direction and amplitude of the initial acquisition, but beyond this point, the task was inherently unpredictable. When performed alone, this task is quite simple, even though the responses are limited to moment-by-moment reactions to observed error. Thus, interest in proficiency on this task is limited to dual-task conditions.

RESULTS AND DISCUSSION

The measures of overall performance on the primary tracking task are RMSE in the single-task segment of the trial (RMSE1), and RMSE in the dual-task segment (RMSE2). The RMSE1 was calculated for the period from the beginning of the trial until the targets appeared on the top display. The RMSE2 was calculated from the time the subject pressed the button on the right joystick, thereby initiating the target-acquisition task, until the target-acquisition task was completed. The overall performance measures on the target-acquisition task are acquisition time (AQTIME), measured from the initiation of the task until the subject pressed the button on the left joystick, and RMSE from that point until the end of the acquisition task (AQRMSE). The accuracy of the initial acquisition was also calculated, but inspection of these data revealed that instances in which the target was not within the boundaries of the sight were extremely rare. No further analyses of these data were performed. It should be noted that there were very few instances where a subject initiated the acquisition task when it was inappropriate (i.e., the catch trials), or where a subject failed to initiate the acquisition task within the specified time limit. Data from the few trials where a subject performed inappropriately are not included in the analyses. Data from the catch trials are also excluded from the analyses. The analyses focus on blocks 2-4 of day 2; block 1 of day 2 is omitted because of potential warm-up effects. All RMSE measures are expressed in the coordinate units of the graphics system which controlled the displays.

The group means on RMSE1 are shown in Figure 2. There were no significant differences between the groups or across blocks. Examination of these means suggests that single-task proficiency on the primary tracking task was stable and roughly equal for all groups. This pattern was not the case for dual-task proficiency. The group means on RMSE2 are shown in Figure 3. The whole-task group showed a steady improvement (i.e., decreased RMSE2) across blocks 2-4, whereas the part-task groups did not. The means for the part-task groups are somewhat misleading because they are inflated by extremely high RMSE2 scores on a few trials in which the subject lost control of the primary tracking task. That is, the subject did not stabilize the cursor position on the primary task before attending to the target-acquisition task. Consequently, the cursor moved farther and farther away from the road, and in some instances, it disappeared from the display. Three of the four subjects in each part-task group lost control of the primary task on at least one trial in blocks 2 and 3. This action produced heterogeneous within-group variances for blocks 2 and 3; inferential tests are therefore inappropriate. By block 4, all subjects were able to maintain control over the primary task. The difference between groups at block 4 is significant ($F = 4.89$; df = 2, 9; $p<0.05$).

It is worthwhile to note that, by block 4, there was virtually no overlap of the subject means in the whole-task group with the subject means in the part-task groups; the highest subject mean in the whole-task group and the lowest subject mean in the part-task groups were roughly equal. Thus, there was a whole-task training advantage for dual-task performance of the primary tracking task, and this advantage became more pronounced across practice on day 2.

The group means on AQRMSE are shown in Figure 4. The group effect is significant ($F = 5.89$; df = 2, 9; $p<0.05$). Post hoc contrasts reveal that the part-task groups were significantly better than the whole-task group for blocks 2 and 3, but the difference at block 4 was not significant. Thus, there was a part-task training advantage for the target-acquisition task, but this advantage became less pronounced across practice on day 2. There was apparently no additional advantage from the extra practice provided for group 3.

There were no differences among the groups on AQTIME. The group means on this measure are shown in Figure 5.

It is important to note that the differences between the groups on RMSE2 and AQRMSE cannot be readily explained by arguing that the two tasks were allocated different priorities by the groups. The whole-task group actually improved on both tasks throughout day 2; both part-task groups remained about the same on both tasks. If the whole-task group merely gave higher priority to the primary tracking task while the part-task groups gave higher priority to the target-acquisition task, then one would not expect the whole-task group to simultaneously increase its advantage on the primary task and decrease its disadvantage on the acquisition task. Although there could have been differences in priorities, it is not clear how the whole-task group's priorities could allow performance of both tasks to improve, while the part-task groups' priorities did not allow performance of either task to improve. A more reasonable interpretation is that the whole-task training given group 1 allowed the development of a response organization which accommodated the demands of both tasks. As this organization developed, performance on both tasks improved. The part-task

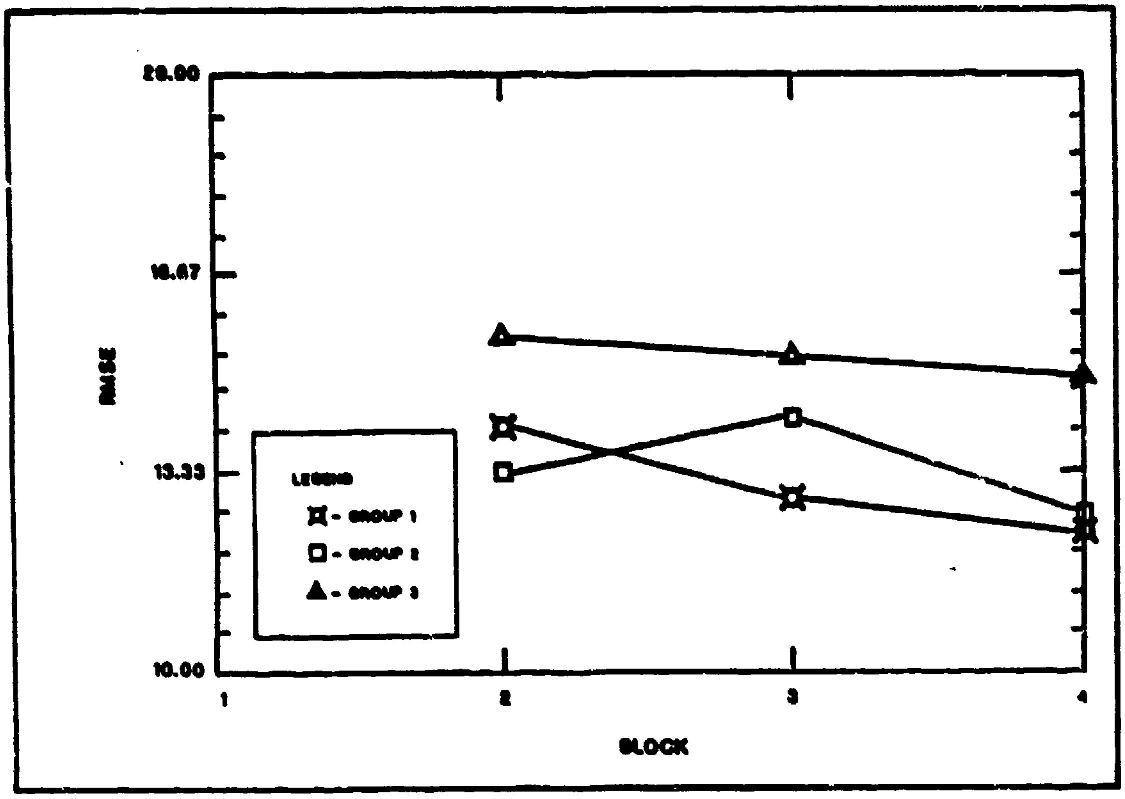

Figure 2. Primary tracking task: Mean RMSE for single-task segment.

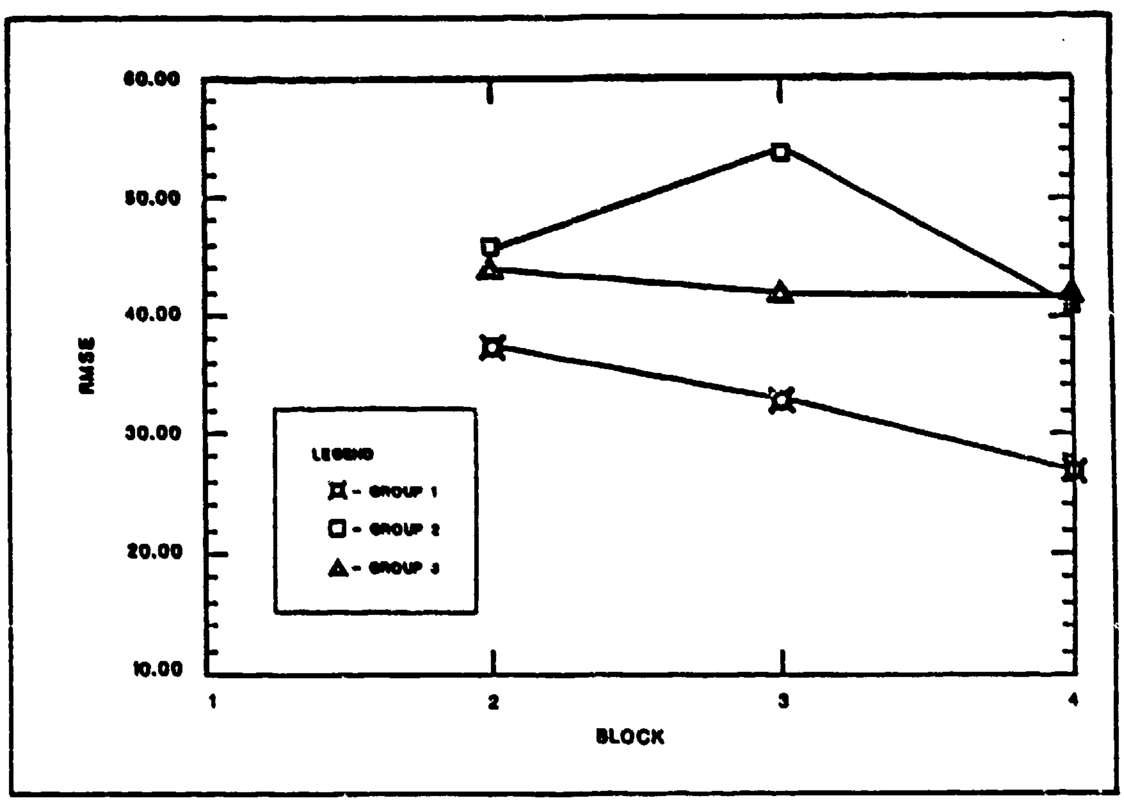

Figure 3. Primary tracking task: Mean RMSE for dual-task segment.

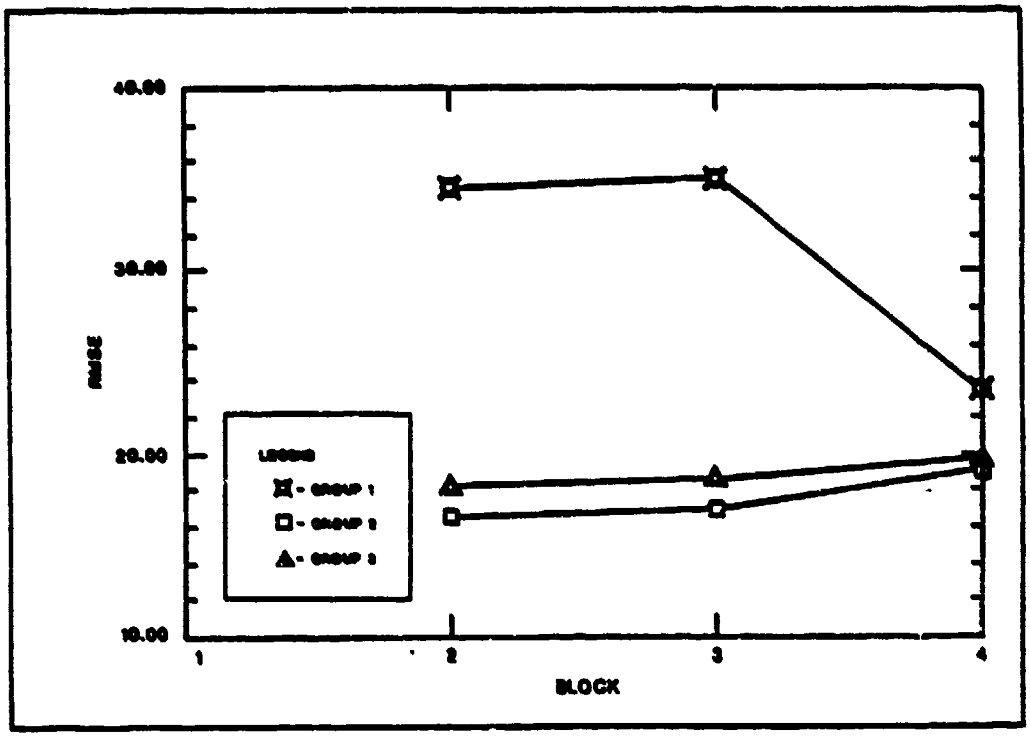

Figure 4. Target acquisition task: Mean RMSE after initial target acquisition.

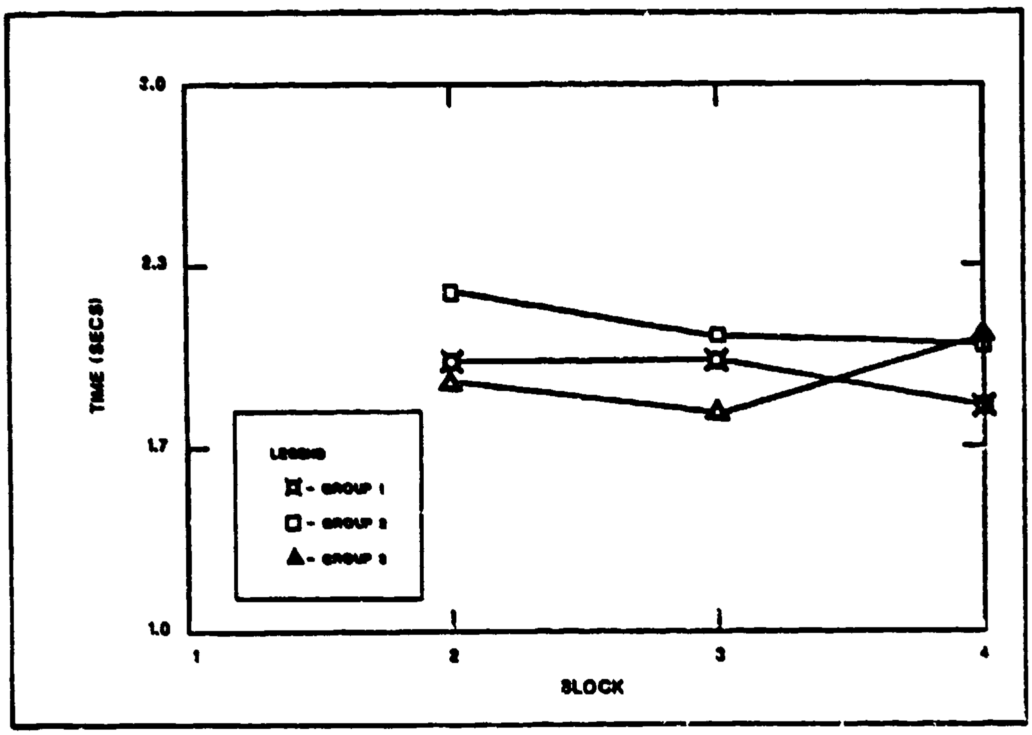

Figure 5. Target acquisition task: Mean time required for initial target acquisition.

training given groups 2 and 3 provided an initial advantage for performance of the target-acquisition task, perhaps by simply allowing these subjects to become well-acquainted with the typical dynamics of the task. But the part-task training did not promote a response organization which accommodated the concurrent demands of both tasks, and no further improvements in proficiency were possible without an appropriate organization.

Any assessment of response organization is necessarily indirect. The available data are simply the frequencies and magnitudes of different types of responses, such as leads and lags in the temporal domain, and undershoots and overshoots in the spatial domain. An assessment of response organization for a given point in practice is largely limited to a description of the relationships between these different types of responses and overall performance. Assessment of response organization development with extensive practice can be more sophisticated, but requires a much larger sample size than was possible here.

The response organization in the primary tracking task is of principal interest here. The target-acquisition task did not permit anticipation of responses to any great extent, except that the direction (and to some extent the amplitude) of the initial acquisition could be inferred from the target array presented on the primary tracking task display. Beyond that point, the task was inherently unpredictable. The primary tracking task was entirely predictable, due to the repetitiveness of the input function and the preview of the display. Thus, the response organization for single-task performance could be expected to develop rather quickly. The issues to be addressed are as follows: (1) the nature of the impact of dual-task conditions on response organization; (2) the extent to which responses in the dual-task condition were organized, and whether this organization (if present) is different from single-task organization; and (3) whether there are any differences between the groups in response organization that can be attributed to differences in training. A reasonable assumption is that the timing of responses on the primary tracking task is the locus of disruption in dual-task conditions, because the unpredictable target-acquisition task required frequent diversion of visual attention to the acquisition display even if no manual response was required. With a constantly changing input function and first-order control on the primary task, the timing of control movements was probably the major determinant of overall performance. When visual attention was diverted, proper timing was undoubtedly more difficult. Therefore, the temporal response organization is the focus of the following assessment.

The temporal organization of responses in the primary tracking task was assessed as follows. Cursor positions for a complete period of the input function (6.7 s) in the single-task segment of a trial were examined and changes in the direction of cursor movement (i.e., the output signal) were identified. The input function during this period had six changes in direction. The changes in the output signal direction were classified according to whether they preceded changes in the direction of input function (LEADS), were in synchrony with changes in the input function (SYNCS), or followed changes in the direction of the input function (LAGS). A fourth category was used for instances in which no response was made to a change in the direction of the input function (NOMOVES). Cursor positions for an identical period of the input function in the dual-task segment of a trial were subject to the same analysis. The starting and ending points of the input function period were carefully chosen,

so that the analyzed movements would be free of extraneous influences. The period analyzed for the single-task segment began about 4.0 s after the trial started and ended at about 10.7 s into the trial, thereby excluding any inadvertent movements which might have been produced by an off-center joystick position at the beginning of a trial, and any movements which might have been influenced by the appearance of the target array 15 s into the trial. The period analyzed for the dual-task segment began about 24.1 s into the trial and ended about 30.8 s into the trial. The beginning of this period was about 9.1 s after the target array was first presented, thereby allowing more than enough time for a subject to examine the array, initiate the second task, perform the initial acquisition, and then begin to perform both tasks concurrently. The mean percent of each response type (LEADS, SYNCS, LAGS, and NOMOVES) in the single-task and the dual-task conditions is shown for each group and block in Table 2.

TABLE 2. RELATIVE FREQUENCY OF EACH RESPONSE TYPE*

		Single-task segment (%)			Dual-task segment (%)		
			Block			Block	
Group	Variable	2	3	4	2	3	4
1	LEADS	12.8	15.7	9.0	18.8	18.3	19.2
	SYNCS	54.8	58.2	58.2	22.5	26.0	36.5
	LAGS	29.5	25.3	32.7	42.6	40.0	33.3
	NOMOVES	2.9	0.8	0.1	16.1	15.7	11.0
2	LEADS	12.2	10.5	12.2	19.8	17.0	14.2
	SYNCS	65.3	61.8	62.2	36.5	41.0	41.0
	LAGS	20.0	23.7	25.0	21.5	28.3	33.0
	NOMOVES	2.5	4.0	0.6	22.2	13.7	11.8
3	LEADS	22.5	20.8	16.7	20.5	22.2	19.2
	SYNCS	46.5	54.8	57.0	31.3	29.5	27.7
	LAGS	27.8	23.7	23.3	34.7	33.0	31.7
	NOMOVES	3.2	0.7	3.0	13.5	15.3	21.4

*Frequencies were computed for one complete period of the input function within each segment so that they would be comparable. Responses during other portions of each segment are not included.

Overall, the groups are quite similar in each category, and there are no pronounced trends across blocks. The major differences are between single-task and dual-task performances. The majority of changes in the input signal direction were accompanied by synchronous changes in the output signal direction in the single-task segment; this was not the case for the dual-task segment. There were few instances of NOMOVES in the single-task segment, whereas in the dual-task segment, typically 10%-20% of the changes in the input signal were not

accompanied by a change in output signal direction at any point. The relative number of LEADS and LAGS tended to be slightly higher in the dual-task segment than in the single-task segment.

Based on the data shown in Table 2, it is clear that the demands of the target-acquisition task impacted performance on the primary tracking task by reducing the number of SYNCS and greatly increasing the number of NOMOVES. There was also a greater tendency to commit LEADS and LAGS in the dual-task segment. These effects, considered alone, are not surprising. The target-acquisition task demanded that visual attention be periodically shifted away from the primary tracking display, thereby reducing the number of SYNCS and increasing the number of LEADS, LAGS, and NOMOVES. An additional consideration is the relationship between overall performance of the primary tracking task and the tendencies to commit these different types of responses.

The correlations between overall performance on the single- and dual-task segments of the primary tracking task and the frequencies of LEADS, SYNCS, LAGS, and NOMOVES during the selected period in each segment are shown for each group in Table 3. These correlations were obtained by computing the correlation between the frequency of each response type and RMSE, and then reversing the sign.

TABLE 3. CORRELATION BETWEEN RAW FREQUENCY OF EACH RESPONSE TYPE AND OVERALL PERFORMANCE[a]

		Condition	
Group	Response type	Single-task segment	Dual-task segment
1	LEADS	0.01	0.28
	SYNCS	0.41	0.47
	LAGS	-0.32	-0.21
	NOMOVES[b]	--	-0.56
2	LEADS	-0.04	0.11
	SYNCS	0.44	0.05
	LAGS	-0.19	0.01
	NOMOVES[b]	--	-0.16
3	LEADS	-0.10	0.10
	SYNCS	0.25	0.35
	LAGS	-0.17	-0.05
	NOMOVES[b]	--	-0.39

[a]Table entries are the correlations between the number of each response type and RMSE, with the sign reversed. Trials in which the task was not performed correctly are excluded, as are all trials in block 1. Typically, each correlation is based on 144 trials (36 per subject).

[b]NOMOVES were quite infrequent in the single-task segment; the associated correlations are omitted.

(Note that these correlations are based on multiple observations per subject and must be interpreted simply as a description of the present data, not as estimates of population parameters.) Comparison of these correlations between groups and conditions suggests that the response organization was different in the single-task vs. dual-task segments, and that the groups differed in the extent to which their responses were well organized in the dual-task segment. The correlations in the single-task segment are similar for all groups--the positive correlation of the number of SYNCS with overall performance is fairly strong, and there is a moderate, negative correlation between the number of LAGS and overall performance. The correlation of overall performance with the number of LEADS is about zero. This pattern makes sense--one would expect the number of SYNCS to be positively correlated with performance, and for the number of LAGS to be negatively correlated with performance. The near-zero correlation of the number of LEADS with overall performance is also understandable, in that, if a LEAD was committed, the error induced by the LEAD could quickly be eliminated by slowing the rate of change in the output signal. The error induced by a LAG, however, could not necessarily be eliminated by increasing the rate of change in the output signal, because the maximum obtainable rate in the output signal was roughly equal to the maximum rate present in the input signal.

The patterns of correlations in the dual-task segment are somewhat different from those obtained for the single-task segment. In particular, note that the correlations for group 2 (part-task practice group) are all near zero, indicating that there was no systematic effect (positive or negative) of any response type for this group. Even the number of SYNCS has a near-zero correlation with performance. In contrast, the whole-task practice group (group 1) shows a fairly strong positive correlation between SYNCS and overall performance, a strong negative correlation of NOMOVES with performance, and a moderate negative correlation of LAGS with performance. Furthermore, the number of LEADS is positively correlated with performance, suggesting that group 1 subjects had learned to make beneficial anticipation of changes in the direction of the input signal. A reasonable speculation is that these subjects may have learned to commit a LEAD before switching their visual attention to the target-acquisition display during the dual-task segment. The pattern for group 3 suggests that their responses were somewhat better organized than group 2, but not nearly as well organized as group 1.

The obvious differences in the pattern of correlations for groups 1 and 2, for the dual-task segment, suggests that the whole-task practice performed by group 1 allowed their responses to become organized to some degree, whereas the part-task practice performed by group 2 did not facilitate the development of a response organization appropriate for the dual-task segment of whole-task performance. Further evidence on the differences between these two groups, and the different organizations characteristic of performance in the single- vs. dual-task segments, is obtained by examining the correlations between the mean number of each response type and mean overall performance, averaging across all trials within blocks for each subject. These correlations are shown in Table 4. Whereas the correlations in Table 3 reflect the relationship between the number of each type of response on a given trial and overall performance on that trial, the correlations in Table 4 indicate whether the subjects who tended to perform better in a given block also tended to commit greater or fewer numbers of each response type. The effect of the averaging is to reduce the influence of unsystematic components of variance (i.e., error variance), thereby allowing the

correlations to more accurately reflect the systematic relationships between overall performance and the frequencies of each response type.

TABLE 4. CORRELATIONS BETWEEN MEAN FREQUENCY OF EACH RESPONSE TYPE AND MEAN OVERALL PERFORMANCE*

		Condition	
Group	Response type	Single-task segment	Dual-task segment
1	LEADS	-0.57	0.67
	SYNCS	0.77	0.90
	LAGS	-0.15	-0.77
	NOMOVES	-0.54	-0.88
2	LEADS	-0.36	0.48
	SYNCS	0.84	-0.12
	LAGS	-0.61	-0.24
	NOMOVES	-0.69	0.08

*Table entries are the correlations between the mean frequency of each response type and mean RMSE, with the sign reversed. Means were computed from each subject on blocks 2-4.

The pattern of correlations in Table 4 is quite clear. In the single-task segment, better performance was strongly associated with greater numbers of SYNCS and fewer numbers of LEADS, LAGS, and NOMOVES; this is true for both groups. In contrast, better performance in the dual-task segment was strongly associated with greater numbers of SYNCS and LEADS and fewer numbers of LAGS and NOMOVES for the whole-task group. The part-task group did not show this pattern, except that better performance was associated with the greater number of LEADS. The other correlations for this group are quite low, even though the influence of other sources of variance was reduced by averaging within blocks. It appears that the dual-task response organization for group 2 was simply not well developed.

In summary, part-task practice of a simple target-acquisition and tracking task was found to provide an initial advantage on that task during dual-task performance, although the advantage was short-lived. This task was inherently unpredictable and thus did not allow anticipation of responses. Performance of a complex tracking task which did encourage anticipation was found to benefit from whole-task practice. The whole-task condition was arranged so that the complex task was performed alone at the beginning of a trial, followed by a period in which the target-acquisition task was added. A more detailed analysis of performance of the complex task suggested that different response organizations were appropriate for the single- vs. dual-task segments, and that the dual-task organization was far better developed in the whole-task practice group than in the part-task groups.

CONCLUSIONS

In retrospect, it seems likely that the most effective training regimen would have been one in which the target-acquisition task was practiced alone, followed by training of the whole task. This regimen would provide both the part-training advantage for the acquisition task and the whole-training advantage for the primary task.

Tasks which do not facilitate response organization, and which must be performed in dual-task conditions, may benefit from training in single-task conditions. This benefit may simply be a matter of allowing subjects to become acquainted with the dynamics of the task and to learn its typical properties; there is little else to be learned. Extensive practice on such tasks is probably not required.

Tasks which do facilitate response organization, and which must be performed in dual-task conditions, may benefit from training in the dual-task conditions. The response organization which is promoted by single-task practice may be inappropriate for the combined demands of the dual task.

The assumption that performance in dual-task conditions is primarily a function of single-task proficiency should be reconsidered. The fact that different response organizations may be appropriate for single- vs. dual-task conditions implies that there is not necessarily a direct, causal link between single-task proficiency and dual-task performance.

Human performance in tracking tasks can be enhanced in two primary ways: (1) designing the task so that response organization is facilitated; and (2) providing training regimens which allow an appropriate response organization to develop and stabilize.

RECOMMENDATIONS

The interpretive framework offered earlier, and the principles derived from it, are based on a synthesis of theoretical constructs and empirical findings from a wide variety of studies. Further research is needed to allow assessment of the derived principles and the predictions offered by the framework. With additional refinement, it is possible that the framework could produce a well-developed theoretical perspective which embraces both the results and processes of the development of skill. Pursuit of this goal requires a program of experimental and correlational research which uses a variety of tracking tasks, fairly extensive practice regimens, and relatively large samples. The first stage of this program should concentrate on experimental manipulations which affect the superdiagonal form of the correlation matrix and the pattern of correlations in the first off-diagonal. Previous research has tended to neglect the effects of properties of the control mechanism on practice requirements, and should be included in the first stage of this program. When the factors which affect the correlation matrix are better understood, latent variable models of the variance-covariance structure may be developed and tested with powerful confirmatory analysis techniques.

A second area in which further research is particularly promising is response organization in dual-task conditions. We recommend that the whole-task configuration used in the present research be modified to include three segments: single-task performance of one task, followed by dual-task performance, followed by single-task performance of the second task. Such a whole task will allow assessment of proficiency in both components for single- and dual-task conditions throughout practice. Two particular issues were left unresolved in this research and should be addressed. First, the response organization which characterized dual-task performance in the whole-task groups was very likely still developing at the termination of practice on day 2. It is not clear whether this alternate organization would eventually become more similar to the single-task organization. Second, it is not clear whether the apparent lack of a systematic dual-task response organization for the part-task groups was simply a matter of insufficient whole-task practice, or whether the extensive single-task practice may have actually impeded the development of a dual-task organization in the whole-task condition. Extending the practice regimen and increasing the sample size should help address both issues.

We also recommend that further research in dual-task performance is needed to address patterns of proficiency and response organization in conditions where both tasks facilitate response organization. The evidence is clear that human performance in tracking is enhanced when the task is designed to facilitate response organization. It is not clear whether additional design considerations should enter in when designing a multiple-task environment, based on the facilitation of appropriate response organizations. If so, these considerations are not clearly known at this time. Multiple resource theory offers an established starting point, but the possibility that response organization can compensate for resource competition, given properly designed tasks, has not been explored. Such research would aid the design of complex environments and the development of theories of human performance in these environments. Again, we recommend that the pursuit of these goals must be based on a program of experimental and correlational research, using a variety of tasks, extensive practice, and large samples.

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